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PROCEEDINGS OF THE

WATER HARVESTING SYMPOSIUM

PHOENIX, ARIZONA, MARCH 26-28, 1974

February 1975

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SESSION I--Herman Bouwer, Chairman

WATER HARVESTING--2000 B.C. to 1974 A.D.

Lloyd E. Myers[1]

INTRODUCTION

This water harvesting symposium is a highly significant event. It is, to my knowledge, the first conference devoted entirely to the subject of water harvesting. In the past, we have found individual papers on water harvesting given at meetings of engineering societies or scientific societies. Unfortunately, the audiences at those meetings were primarily interested in subjects such as irrigation, grass production, or soil physics. As a consequence, our papers have usually failed to attract significant interest. Of even more importance, information on water harvesting has been presented in bits and pieces that have not composed a complete package for consideration by potential users. Hopefully, at this conference, we will have comprehensive discussions of all phases of water harvesting, including the most recent developments in water harvesting research. The proceedings of this symposium should allow individuals planning water supply projects to give reasonable consideration to the potential use of water harvesting for their particular needs. We also hope that this symposium marks the beginning of improved communication among all individuals interested in water harvesting so that our accomplishments in the future will exceed our accomplishments of the past.

I assume everyone here knows the meaning of the term "water harvesting," but perhaps the origin of the term is not so well known. To the best of my knowledge, the term was first used by Geddes of the University of Sidney. He defined water harvesting as "the collection and storage of any farm waters, either runoff or creek flow, for irrigation use" (5). I generalized the definition to say that "water harvesting is the practice of collecting water from an area treated to increase runoff from rainfall and snowmelt." More recently, Currier has defined water harvesting as "the process of collecting natural precipitation from prepared watersheds for beneficial use " (2).

HISTORY OF WATER HARVESTING

Before the development of gasoline engines and electric motors, water harvesting was a fairly common practice in a number of arid and semiarid regions. Evenari and his colleagues have described water harvesting systems in the Negev Desert, which are thought to have first been built about 4,000 years ago (3). These systems involved clearing hillsides to smooth the soil and increase runoff, and then building contour ditches to collect the water and carry it to lower lying fields where the water was used to irrigate crops. By the time of the Roman

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Empire, these runoff farms had evolved into relatively sophisticated systems. There is evidence that less complicated systems were used about 500 years ago by ancient peoples in what is now the Mesa Verde National Park in southwestern Colorado.

In terms of more recent history, collection and storage of runoff from the roofs of houses is a practice that is still used in some regions, although the development of central water supply systems has caused this practice to be abandoned and forgotten in many parts of the world. Some catchments have been built in the form of roofs without a house under them. In 1929, Kenyon described such a catchment built of galvanized sheet iron at a location in Australia (7).

The next significant development was the construction of roaded catchments, which were described by the Public Works Department of Western Australia in a bulletin published in 1956 (12). These are called "roaded catchments" because the soil is graded into a series of parallel roadways or gently sloping ridges that drain into the ditches separating them. These ditches convey the collected water to a storage reservoir. Apparently, several thousand acres of these catchments have been installed to obtain farm water supplies.

A small number of catchments were built of sheet steel and concrete in the United States during the 1950's to provide water for livestock and wildlife. The most significant development in the 1950's was the pioneering work of Lauritzen in evaluating plastic and artificial rubber membranes for the construction of catchments and reservoirs (8). Lauritzen's work has served as the basis for the installation of numerous butyl rubber catchments, including more than 300 catchments and reservoirs in the State of Hawaii.

In 1961, I proposed that we take an entirely different approach to the problem and investigate methods of utilizing the soil itself as the catchment structure (9). At the U.S. Water Conservation Laboratory, in 1959, we had begun to investigate materials that caused the soil to become hydrophobic or water repellent. This work seemed promising. Beginning in 1960, our work was gradually expanded to include sprayable asphaltic compounds, plastic and metal films bonded to the soil, soil compaction and dispersion, and field fabricated asphalt fiberglass membranes.

Early in 1960, research programs in water harvesting were also initiated in Israel by Hillel and at the University of Arizona by Cluff. Hillel's work now relates primarily to soil smoothing and runoff farming (6). Cluff has done a considerable amount of work on the use of soil sealing with sodium salts and on gravel-covered plastic membranes (1). The most recent innovation in the construction of catchments appears to be the use of granulated wax spread over the ground surface so that the sun will melt the wax and cause it to flow into the soil. The resulting wax coating causes the soil, for some as yet unknown period of time, to become both water repellent and stabilized.

After having presented these brief and incomplete excerpts from water harvesting history, as I know it, I would like to quote from a paper published in 1964, in which I attempted to outline the objectives we should strive for in research on water harvesting catchments (10):

> "Conventional materials which have been used for water harvesting structures have included portland cement concrete, asphaltic concrete, soil cement, corrugated sheet metal, and asphalt impregnated fiber planking. These materials are intended to provide considerable structural integrity as well as an impermeable surface. Such materials were not developed for water harvesting but for other uses such as road building and reservoir lining. Most of them require the use of heavy

construction equipment. Those which may not require heavy construction equipment require transportation of large quantities of materials from a source of supply to the construction site. Costs and performance of completed structures have varied widely because of variations in design and in transportation and labor requirements. The lowest costs for durable structures made of conventional materials have been too high. Lower costs for water harvesting structures can be obtained only by developing new materials and construction procedures which reduce requirements for materials, equipment, and labor. This can be done by research and development aimed specifically at the performance requirements for water harvesting structures. These are not the same as performance requirements for road building and reservoir lining. Some of the desirable characteristics of materials for catchment aprons are as follows:

1. Runoff from the structure must be nontoxic to man and animals.
2. The surface of the structure should be smooth and impermeable to water.'
3. The structure shoud have high resistance to weathering damage and should not deteriorate because of internal chemical or physical processes such as crystallization.
4. The structure need not have great mechanical strength but should be able to resist damage by hail or intense rainfall, wind, occasional animal traffic, moderate flow of water, plant growth, insects, birds, and burrowing animals.
5. The material used should be inexpensive, on an annual cost basis, and should permit minimum site preparation and construction costs.
6. Maintenance procedures should be simple and inexpensive.

All of these characteristics may not be obtained with anyone material and the best structure may often be obtained by using a combination of materials.

We are now wiser than I was in 1964. We now know that it is usually necessary to forego one desirable characteristic in order to achieve another, particularly when the overriding objective is lower cost.

STORAGE

Because of the intermittent nature of runoff from precipitation catchments, storage must be an integral part of any water harvesting system. When water harvesting techniques are used for runoff farming, the storage reservoir will be the soil itself; but when the water is to be used for livestock, supplemental irrigation, or human consumption, a storage facility of some kind will have to be provided. We have made some progress in reducing seepage losses from reservoirs by soil treatments, such as by lining with plastic or rubber film, or by using tanks of concrete or steel. Procedures have been developed for utilizing relatively low-cost structures, such as metal grain bins, by lining them with plastic or rubber sheeting. We have found that it is usually less expensive to reduce evaporation losses with tank covers than to attempt offsetting these losses by increasing the size of the uncovered storage structure. We have evaluated a number of materials for reducing evaporation, including floating granular materials, floating covers of plastic or artificial rubber, and floating membranes of soft wax. The fact is, however, that we have devoted considerably less effort to the problem of water storage than to the problem of catchment construction, and our progress in reducing the cost of water storage is noticeably less than our progress in reducing the cost of water collection.

SYSTEM DESIGN

Selection of the lowest cost catchment treatment can sometimes be a mistake. Smoothed soil catchments produce water at very low cost, but they do not provide runoff from the small rains that characterize the low rainfall periods of the year. A large and expensive structure might have to be built to store water for use during the period when no runoff occurs. The cost of a smoothed soil catchment, plus the large storage required, could be greater than the cost of a more expensive catchment, which provides runoff during the low rainfall period, plus a smaller storage structure. On the other hand, if adequate low-cost storage were already available, the smoothed soil catchment could provide the lowest cost total system.

Procedures have been recently developed for determining the lowest cost combination of catchment size and storage size for any given combination of unit construction costs for catchment and storage, catchment efficiency, water demand schedules, and precipitation patterns (4). As yet, this procedure has not been utilized to determine the reliability or economic feasibility of water harvesting installations.

WATER QUALITY

The quality of water obtained from catchments is not ordinarily a problem for livestock or for irrigation, but it must be considered when the water is to be consumed by humans. Water obtained from unstabilized bare soil catchments will contain suspended sediment and colloidal material that may make filtration desirable before human use. Water running off an asphalt surface can be discolored by oxidized asphalt, particularly in arid regions. The discolored water is normally odorless, tasteless, and is readily consumed by cattle. It is believed to be harmless to humans, but it cannot be recommended for human consumption until this is proven. Any type of catchment is subject to contamination of runoff water by animals. Animal traffic on the catchment will result in contamination of the water with fecal material. Catchments and reservoirs for human use should be fenced to eliminate large animals. Contamination by small animals may not be a problem, but this possibility should not be overlooked. When necessary, the water can be purified with relatively simple systems involving sterilization followed by sand and charcoal filtration.

RUNOFF FARMING

When rainfall occurs just before or during the crop growing season, but is insufficient in quantity for good crop growth, water harvesting can be used to irrigate and produce some varieties of grain, vegetables, fruits, and nuts. This procedure is called "runoff farming." Considerable work has been done in Israel to determine suitable plant varieties. Sorghum, melons, and cucumbers have been successfully grown by the University of Arizona in small plots irrigated by water harvesting techniques. Similar attempts to grow melons near Phoenix failed, partially because of inadequate rainfall but mostly because soil at the study site would not store enough water to support the plants between rainfalls.

Success in runoff farming will depend upon many factors. When trees, shrubs, and grain are grown, distribution of rainfall may not be critical. When some annual crops are grown, rain must occur at the beginning of the growing season and possibly at intervals thereafter. There must also be a soil profile that can store adequate quantities of water. A computer program has been developed at the University of Arizona to consider rainfall, soil water storage, and crop evapotranspiration. From these data, the program estimates probable crop yields. Crop yields will also depend upon insect and disease control, uniform distribution of harvested water to the plants, favorable germination, and crop varieties adapted to intermittent periods of wet and dry soil.

CONFLICT WITH OTHER LAND USES

Some unkind and uninformed critics have assumed that the proponents of water harvesting intend to pave vast areas of land and to "tinplate" our mountains. Nothing could be further from the truth, but we must give consideration to possible conflicts with other land uses.

Water harvesting installations in the United States have been relatively small up to the present time and have occupied very little land. Larger installations will surely be built in the future to obtain water for domestic use and other purposes. These catchments may cover several hundred acres, and the question of alternative land uses will arise. The principal large area land uses alternative to water harvesting could be timber production, grazing, and recreation.

The largest conceivable areas that might be converted to catchments would constitute only a minute fraction of the millions of acres of timber. An evaluation of water versus timber values, using data from the Beaver Creek study in Arizona, indicates that water can be the more valuable product (11). We might also consider a situation where a decision has been made to manage forested lands to increase water yield. Such management, in some areas, would include clearcutting of alternate blocks, for example, clearcutting 80 acres of timber on Workman Creek increased runoff from 264 to 352 acre-inches, or by 88 acre-inches. Four acres of catchment at 90-percent runoff efficiency would produce 115 acre-inches in that 32-inch annual rainfall area. This means that more water could be obtained by building 4 acres of catchment and leaving 76 acres of trees. Many other factors must be considered, but the preceding data suggest that intensive water harvesting procedures might actually be used to preserve forested lands in areas where water yields must be increased.

As with forested areas, the amount of land diverted to catchments would be a very small part of the available grazing land. Utilization of rangelands is often limited by a lack of water. Development of economical water harvesting practices for livestock water supplies should permit improved range management practices and should increase the carrying capacity of many rangeland areas. Such increased carrying capacity would more than compensate for any rangeland areas converted to large-scale water harvesting for offsite uses.

There is no conflict between recreation and water harvesting. To the contrary, recreation should benefit substantially from water harvesting. There need be no eyesores or damage to scenery because catchments can be made any size, shape, or color and can be camouflaged or hidden from view if this is desirable. Water harvesting can be used to establish and maintain landscaping vegetation at strategic locations. Catchments have been used successfully to provide water for wildlife, and this practice is increasing. Drinking water for human visitors to some Hawaiian recreational areas is obtained from catchments. This practice can be used to make parks in our arid regions more hospitable and attractive. Water harvesting need not detract from, but can significantly improve, many of our recreational resources.

SUMMARY

Ten years ago I predicted that wide-scale application of water harvesting principles would develop within the next decade. Although a goodly number of water harvesting systems have been built, it would be difficult for me to pretend that wide-scale application has occurred. What went wrong?

We might blame the fact that some materials we thought had tremendous promise have failed the unkind tests of field application. Thin plastic films, which were supposed to resist weather damage for 20 years, failed because they shrank. Chemicals, which performed beautifully in waterproofing sandy soils, failed on soils containing appreciable quantities of silt and there were many other disappointments. On the other hand, we have developed materials and methods that do reduce costs and installation difficulties and that have not failed in long-term field trials under difficult conditions.

The fact is that we have done our research on separate components of water harvesting systems, and we have ordinarily reported on the performance of separate components. We have not yet combined the bits and pieces of our research into useable packages that can be considered by potential users. These packages must contain more information than we have yet developed. How reliable are water harvesting systems under different site, climate, and water use conditions? When should water harvesting systems be used in preference to other water sources? How does the potential user decide? Our potential users need much more information than we have as yet provided.

We are quite capable of developing, in the near future, the technical and economic information we must have before water harvesting will receive adequate consideration. I believe that we will do it, and on that basis I am saying once again, but with more conviction this time, that wide-scale application of water harvesting principles will develop within the next decade. There are many locations where water harvesting offers the only opportunity to develop onsite water supplies of good quality, usually at low energy cost. This source of water, based on ancient, but sound, principles clearly deserves increased attention and consideration by water resource planners and investigators. I trust that this symposium marks the beginning of that clearly deserved attention.

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WATER HARVESTING FOR LIVESTOCK IN WESTERN AUSTRALIA

W. J. Burdass[1]

INTRODUCTION

Water harvesting--the collecting, conveying, and storing of precipitation (14, 15)--is widely practiced in Western Australia. From earliest times, water has been collected from the roofs of buildings and stored for domestic use. For at least 25 years, the Public Works Department (PWD) of Western Australia has been treating catchments to increase the inflow into storages for public use (20). The history of water harvesting on farms for livestock water goes back even further, and has been actively encouraged by the Department of Agriculture for half a century (23).

The types of water harvesting practiced in Western Australia, in providing supplies for livestock either alone or in combination, are:

I. Diversions to intercept
    A. Surface flow (5, 8, 11, 24)
    B. Subsurface flow

II. Surface treatments
    A. Mechanical
        1. Stripping, leveling, and compaction
        2. Profile inversion
    B. Chemical
        1. Using petroleum compounds (9, 16)

Hydrophobic chemicals (9, 17), colloidal dispersants (9, 15), and impervious films (17, 19) are not used, although hydrophobic chemicals (22) and colloidal dispersants 2/ are being tested.

Background Information

The farming areas of Western Australia are located in the southwest corner of the Australian continent and lie roughly southwest of a line drawn from Geraldton on the west coast to Esperance on the south. This is the area treated in this paper.

Climate

The climate is of a Mediterranean type with wet, cool winters and hot, dry summers. Average annual rainfall ranges from 1,400 mm near the coast, at the extreme southwest tip of the State, down to 300 mm inland. The isohyets run approximately parallel to the coast (fig. 1). Most rain falls in winter, but occasional high-intensity storms occur in

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1/ District Soil Conservation Adviser, Soil Conservation Service, Branch, Department of Agriculture, Katanning, Western Australia 6317.

2/ Laing, I. A. F., Research Officer, Soils Branch, Department of Agriculture, Western Australia, South Perth. Private communication. 1974.

summer. There is no snowfall except for very occasional light coverings on the Stirling Range in the south, which is of no consequence.

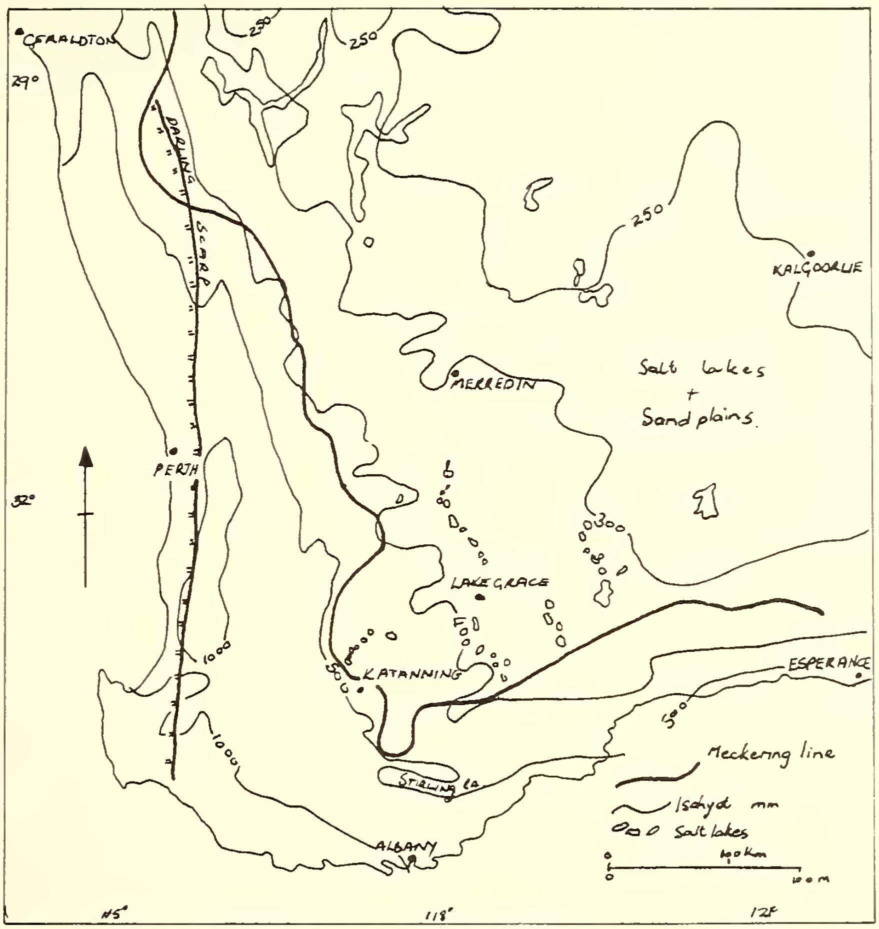

FIGURE 1.--Map showing rainfall and major topography in southwest Western Australia

Temperatures show marked diurnal and seasonal fluctuations. The average maximum temperature ranges from 20° C near the coast to 25° inland; the average minimum is more uniform, being 10° or 11°. Frosts do occur in most areas but are not sufficiently severe to affect soil structure. Annual evaporation ranges from 900 to 2,000 mm. The average length of growing season varies from 8 months on the south coast to only 3 months inland.

Geology (12, 13)

The landscape is geologically old. East to the Darling Escarpment (fig. 1), which runs north and south inland from the west coast, it is typical of an old shield landscape. This area was subjected to epeirogenic uplift in the Tertiary period. The plateau has since been dissected by rejuvenated drainage lines west and south of the so-called Meckering line. This line approximates to the 400 mm isohyet. East and north of this line is the zone of "sandplains and salt lakes." The landscape in this zone has low relief and sluggish drainage lines, which, in interaction with the climate, has resulted in the formation of saline ground waters--often at shallow depth (1). In the process of agricultural development, this problem has been accentuated by the replacement of deep-rooted woody, perennial vegetation with shallow-rooted annuals (2) The process continues.

Soils (13)

In the zone of "sandplains and salt lakes," sandy yellow earths and lateritic podzols are found on the broad ridges whilst in the valleys calcareous brown solonized soils are most common; these soils are the heavy "salmon gum-gimlet soils of the Wheatbelt." Formed in association with the salt lakes, by aeolian action, are saline and calcareous mallisols, known locally as snuffy morrel soils. These have an extremely loose consistency.

West of the Meckering line, where the remnant of the old plateau is less extensive but better defined, it carries an ironstone capping. Lateritic soils are commonly found on the sides and bottoms of the valleys in association with red-brown podzols, red-brown earths, and solonized brown soils.

Further west, the ridges become narrower and are often capped with massive ironstone and the soils on the blanking slopes are composed of detrital material derived from the ironstone cap.

To the south of the Meckering line, lateritic podzols and solodized - solonetz are also found with the red-brown earths and solonized brown soils.

Soil type is of importance in determining the availability of storage sites, and also which water harvesting technique, if any, is used. However, whilst the nature of the surface soil is of importance, possibly the most important single factor in determining the success of water conservation techniques in Western Australia is the presence or absence of the pallid zone clay formed under the lateritic cap of the old peneplain. This zone of deep weathering consists of material characterized by quartz grains embedded in a matrix of kaolinized clay. This clay becomes dispersed in water due to the presence of exchangeable sodium in the exchange complex.

In most situations in which they are encountered, the pallid zone clays have the reputation of holding water "like a bottle;" and when used to surface catchments they readily form a crust or skin. The pallid zone clay is widely distributed under many, though by no means all, of the soil types encountered in the agricultural areas of Western Australia.

Farming Type

Mixed farming is practiced over most of the area with greater emphasis on livestock in the wetter western and southern districts and greater emphasis on cereal production in the drier east--the wheatbelt of Western Australia. Wool production is the main livestock enterprize, with beef production playing an ever-increasing role in the wetter districts. Regardless of the type and class of stock, they must all have a reliable year-round supply of water.

Water Supplies

The agricultural areas of Western Australia are not well endowed with natural water supplies. Natural supplies do, however, improve toward the west, and water harvesting is not practiced to any significant extent west of the 850-mm isohyet.

Streamflows, which, because of climate, are ephemeral, are also frequently saline. They are a source of water for stock on some farms in the higher rainfall districts when diluted by recent rains.

The majority of farmers rely entirely on water conserved in excavated tanks for watering their stock. Ground water suitable for stock is found in a few isolated districts (1), whilst some other districts are served by piped supplies reticulated from public storages in the Darling Ranges.

This dependance on water stored in tanks is illustrated by the results of a survey conducted in the area in 1970. 3/ Of 12,777 farms sampled, 75 percent had some 73,714 excavated tanks; only 42 percent of farms had usable bores or wells, and 25 percent had other sources of water such as soaks or lakes. The average capacity of the tanks was 1,1460 m^3. The average total tank storage on farms with tanks was 11,172 m^3.

Maintaining a supply of water in tanks is the problem that has stimulated the development and use of water harvesting practices on farms in Western Australia. The problem tends to become more acute in the districts of lower rainfall but is by no means confined only to these areas. It is compounded by surface soil conditions--as in deep sandplain country--by the ubiquitous occurrence of salt in the landscape and high losses caused by evaporation.

WATER HARVESTING TECHNIQUES

Diverting Surface Flows

The simplest method of water harvesting on farms is to collect and store natural flow. This has been done for many years (24) and is still a common and effective method.

On its own, the excavated tank can collect as well as store water, and whilst in the strictest sense of our definition this may not qualify the "siting" of a tank as a technique of water harvesting it is an essential part of nearly all the water harvesting systems used in Western Australia for providing water for livestock. Thus, when sited to intercept natural flow, the tank dam could be regarded as being the simplest system.

However, when speaking of collecting natural flow, the use of a drain or drains is implied--the drain collecting and conveying the water to the tank for storage. The positioning of the dam in this process can still be vital: Sited low in the landscape may mean the depth of the tank and, hence, its capacity are limited by incipient salt; sited high up in the landscape may restrict the size of the potential catchment; whilst in between problems of unsuitable soils for holding water may be encountered. In each case, the water harvesting project can be jeopardized.

The normal structure for intercepting flows is the contour drain 4/ (5, 8) as used for runoff control to prevent erosion. Indeed, in many situations, contour drains are constructed for the dual purpose of water harvesting and erosion control. They can be used to intercept

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3/ Commonwealth Bureau of Census and Statistics. Water resources on farms at 31 March 1970. 4 pp. 1971. (Mimeographed.)

4/ Also referred to as contour grade banks, bunds, or terraces in various parts of the world.

1. Sheet flow from paddock and bush slopes (8).

2. Localized flow from areas of impervious clay, or rock outcrops.

3. Streamflow from natural drainage channels.

4. Flow from manmade structures such as public roads, farm tracks, farmsteads, and borrow pits from which gravel has been taken for road construction.

Dual purpose banks, designed to collect water from free shedding areas, are built on a grade of 0.3 to 0.5 percent. They are constructed by farmers using their own disk plow (23) or by contractors using road graders (25). The grade along the length of the bank is kept steady or is increased slightly in the direction of the flow. The steeper grade is not normally exceeded because of the danger of erosion in the channel.

Where the natural catchment does not shed water readily and a bank is constructed only as a water harvesting device, the grade along the bank may be adjusted in an endeavor to initiate and maintain flow into the tank (11), without causing erosion in the channel. This is done by surveying the upper end at a steep grade of up to 1.3 percent and progressively reducing the grade in the direction of flow, the last section before discharge into the tank being as low as 0.1 percent. If the capacity of the drain is not increased at its lower end, there is a danger of the bank overtopping following high-intensity storms.

The Soil Conservation Service (5) specifies drains with flat, shallow channels at least 2 m wide at the bottom. The soil taken from the channel is used to form a bank on the downhill side about 0.5 m high when freshly built.

Cutting the channel into clay reduces channel losses. V-shaped channels, whilst running water more readily at low flows are prone to scouring when carrying large flows. For this reason, channels with wide bottoms are preferred.

Contour drains are essentially a means of "enlarging" the area of the catchment shedding water into a given storage. They can also increase the drainage density. Their efficiency can be enhanced if:

1. The channel of the drain is cut down through sandy or friable topsoil into impermeable clay and the clay packed onto the upslope batter of the bank. In this case, the bank and channel serve as "improved" catchment.

2. Contour drains intercept runoff from areas of catchment with smooth impermeable surfaces such as sealed roads or clay capped hills.

Contour drains are of little or no value on catchments with high infiltrability such as deep sand.

Contoured Catchments

Contoured catchments, described by Young (26) and Hollick 5/, are used on steeper slopes in South Australia, but are not in general use in Western Australia. In this catchment, a series of contour drains is used to collect and convey runoff from the intervening areas, which are smoothed and compacted. The contour drains discharge onto a pastured depression or waterway, which takes the water downslope to the tank.

5/ Hollick, M. Technical and economic evaluation of surface treatments for increasing run-off from small rural catchments. Austral. Water Resources Council Proj. 71/37. Rpt. on visit to So. Austral. 7 pp. 1972. (Mimeographed.)

Collecting Drains on Rock Catchments

In the driest zone of the agricultural areas--the zone of "sandplains and salt lakes"--granite outcrops or bosses occur quite commonly on the crests of the broad sandplain ridges (1).

Runoff from many of these outcrops is collected by means of low concrete or masonry walls or gutters built around the lower slopes of the rock (24). The water so collected is conducted along the gutter to a concrete storage tank built on or close to the rock, or to an earth tank sited downslope from the rock.

The water from these rock catchments is noted for its excellent quality. The PWD has constructed harvesting systems of this sort on some of the larger rocks to provide public supplies or potable water.

Pumping From Ephemeral Streams (8)

Salinity problems along valley floors and drainage lines generally preclude the building of onstream storages in most areas east of the Darling Escarpment. However, in the areas that have an annual rainfall of more than 450 mm, ephemeral streamflows, low in salinity, do occur during many winters.

Pumping from these flows to offstream storages is practiced to a limited extent where it is impossible to gravitate water to the storage using a contour drain. Onstream sumps are sometimes constructed to provide temporary storage.

Initial flows in early winter are allowed to flow to waste in order to flush from the system the salt that has accumulated over the summer. Onstream sumps may have to be pumped out to eliminate the salt. It is possible to place the sump off the stream and make a weir arrangement that passes low flows but diverts large ones.

Intercepting Subsurface Flows

From earliest times, settlers discovered that summer moist patches sometimes developed after clearing. These patches were found on lower slopes where subsurface moisture moving downslope, usually at relatively shallow depth, was forced to the surface by an impervious subsoil or by rock.

Where landscape and soil conditions favored, water actually welled to the surface; in others, a shallow excavation 2 to 3 m deep resulted in a supply of good quality water. In a few instances, these "soaks," as they are called, proved to be good reliable supplies for both stock and domestic use. Unfortunately, in most instances they turned out to be unreliable--drying up in the drier years. Still others became salt affected.

In recent times, the catchments of some soaks have been enlarged by digging subsurface drains, and, in the higher rainfall areas, a similar technique has been used to harvest shallow subsurface water. In these wetter areas west of the 450-mm isohyet, waterlogging commonly occurs in winter on the lower slopes of the more dissected landscapes. Surface flow may not occur, but free water does move on the surface of the clay subsoil. The soil profile where this occurs is typically a light-textured topsoil overlying clay as found in podzols, the topsoil being 30 to 70 cm deep. Shallow contour drains do not intercept this water, and to harvest it a drain must be constructed into the clay.

The normal procedure is to excavate a trench down to the clay during the sinking of the hillside excavated tank conventional to the area. This trench is backfilled with the clay spoil taken from the tank. The "wing" becomes an extension of the side embankment of the tank. It may or may not be built up above ground level. Such drains are rarely more than 50 m long. Grade is not critical provided water flows in the direction of the tank. This is a situation where tile drains could be used for water harvesting. However, subsurface drainage is not a normal practice outside the irrigated areas of Western Australia, and machines are not available to lay "tile" or "split" plastic pipes.

Subsurface drains are of no use in years of low rainfall when the soil profile never becomes saturated. For this reason, they have not proved a reliable method of collecting water.

SURFACE TREATMENTS

Mechanical Treatment

Roaded Catchments (3, 21) (fig. 2)

Roaded catchments began as smooth compacted ridges of earth built in parallel, with the furrows between linked to a dam directly or by a tail drain.

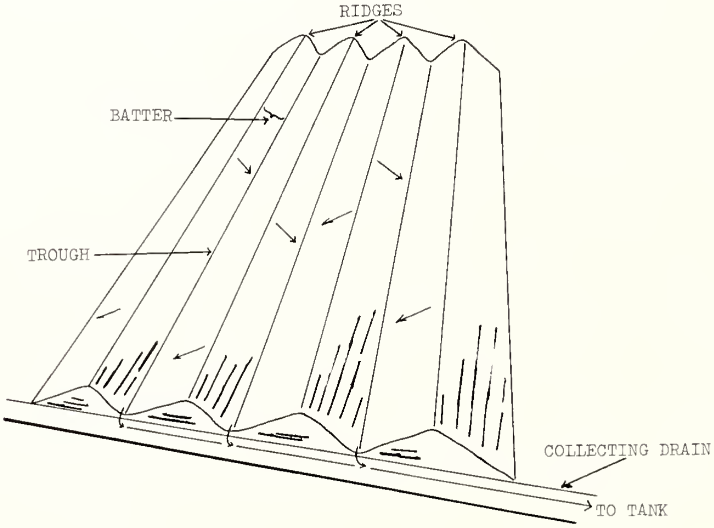

FIGURE 2.--Roaded catchment.

The better farm catchments still retain these characteristics but also have the topsoil completely inverted and buried by an overlay of subsoil clay (7).

Roaded catchments were developed as a water harvesting technique by PWD engineers in the years 1949-52 (21). The idea sprang from observations that the gravel roads found extensively in the rural areas of Western Australia ran water on light falls of rain when adjacent undisturbed areas failed to do so. The technique was first used to improve inflow into tanks constructed as public supplies. It was later adopted for filling farmers' tanks.

Between 1952 and 1955, the PWD constructed 332 catchments aggregating 1,350 acres (21). Since that time, the number of roaded catchments on farms has continued to increase and an accurate count has been lost. The most recent estimate prepared by Laing 6/ in 1973 puts the number of roaded catchments on farms in Western Australia at 2,500, with a probable total area of about 2,000 hectares.

At first, more emphasis was placed on compaction rather than on geometry, and the appearance of the early catchments had a tendency to look like the rural roads. They were built using graders and rubber tired rollers (21).

From 1955 onwards, more and more catchments were built by private contractors, and construction standards tended to drop. By the late sixties, most farm catchments were being constructed by contractors with no technical supervision, rollers were rarely used, and such compaction that was achieved resulted from the tracking of the grader. The efficiency of farm catchments generally declined. This was accentuated in some new land areas by the difficulty of turning up compactible material. Soil profiles of the lateritic podzols and solodized solonetz in these areas are sharply differentiated into light-textured topsoil and clay subsoil. If the drains are not cut into clay, little runoff occurs. When the original spacings (21) are adhered to, ridge spacing is too narrow for this to be achieved.

The importance of exposing subsoil clay was recognized in the late fifties during the development of War Service Land Settlement farms in the Jerramungup and Gairdner River areas. It became practice, on sites with topsoil deeper than 25 to 30 cm, to bulldoze the topsoil off the site before constructing the roads with a grader. Several of the catchments constructed in this manner still function well after a period of minimum maintenance since they were constructed. Others of more recent origin, not cut into clay, have not yielded runoff substantially better than the natural catchment surrounding them.

Three contractors, specialists in the construction of roaded catchments--Syd Harper and Merv Gilchrist at Albany, and Ken Shepherdson at Esperance--appreciated the need to make roads wider in order to expose the subsoil clay. It was in drawing on their experience that Prout (20) was able to tabulate the depth to clay, the distance apart of roads, and the cost per acre.

Frith and Nulsen took this a stage further by producing their formula for achieving clay cover (7) and by simulating a stock water supply system incorporating roaded catchments as an essential component. 7/ In this work, they were aided by the early computer study into the storage life of farm dams by Carder (4). Concurrently, Hollick has been investigating in greater detail the hydraulic design of catchments. 8/

Roaded catchments are the standard means of water harvesting where the infiltrability of the natural catchments is too high for the contour drains to be effective and where the depth to clay or other compactible material does not exceed 35 cm.

Flat Batter Tanks (5, 20) (fig. 3)

Flat batters, or more correctly, flat batter tanks, are combined storage and water harvesting structures in which clay spoil taken from the lower levels of the tank excavation is used to cover the overburden removed from the surface of the excavation.

6/ Laing, I. A. F., private communication, 1973.

7/ Frith, J. L. Interim report on computer model of stock water supply. West. Austral. Dept. Agr., Soil Conserv. Serv. 8 pp. 1972. (Mimeographed.)

8/ Hollick, M. The development of improved catchments for farm dams. Prog. Rpt. (1970-71) Dept. Civ. Engin., Univ. West Austral. 7 pp. 1972. (Mimeographed.)

They were developed in the mid-sixties by farmers and contractors in the Esperance district. The sand and gravelly surface horizons of the lateritic podzols common to that area are frequently greater than 35 cm deep. Difficulty is experienced in constructing effective roaded catchments under these conditions. In the conventional excavated tank, the spoil is formed up on three sides to form an embankment, with internal batter slopes of about 33 percent. On a sloping site, this embankment holds aboveground storage; on a flat site, none. At Esperance, sites are frequently flat.

In the flat batter tanks, the spoil from the excavation is spread on three sites (a three-way push) or four sides (a four-way push) and clay is faced so as to form a smooth, relatively impervious surface, which drains back into the excavation. The batter slopes in the excavation remain at 33 percent; but on the spread batters serving as catchment, they range from 0.5 to 5 percent depending on the original depth to clay, the slope across the site, and the area of the batters.

Whilst no formal standards were set, two common sizes were the 30-m and the 40-m push--the catchment batters extending 30 and 40 m, respectively, from the edge of the excavation, the storage of the dam being of the order 2,000 to 3,000 m^3. Both smaller and larger storages, with correspondingly smaller or larger catchments, have been constructed.

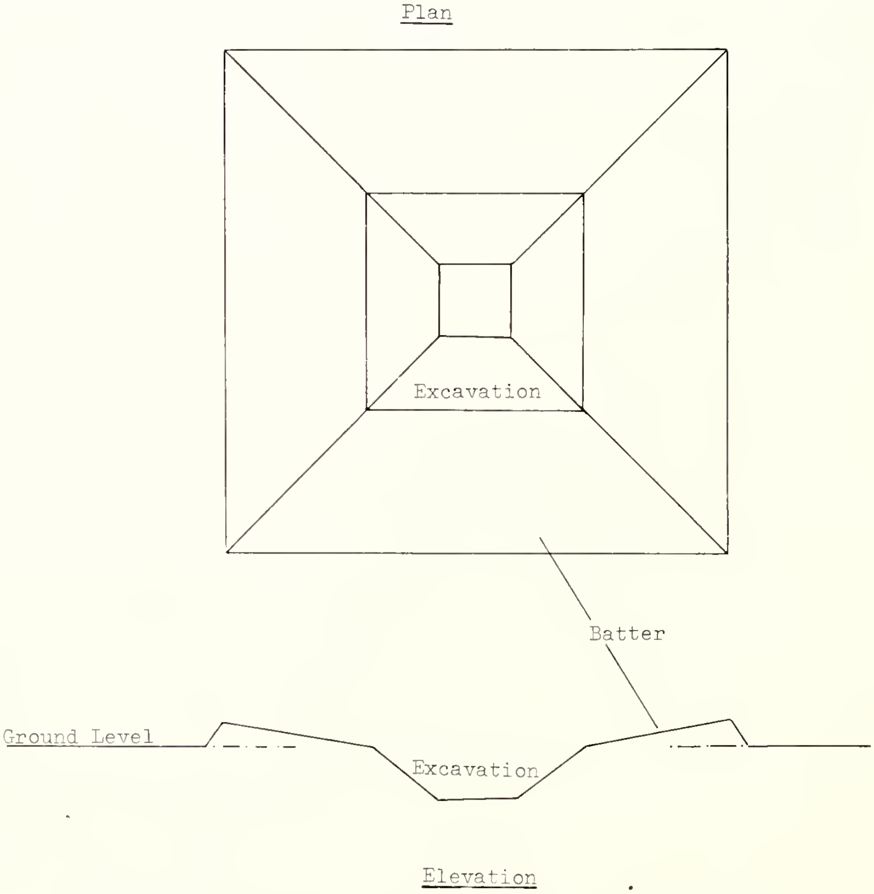

FIGURE 3.--Square or four-way flat batter tank.

Circular Flat Batters (fig. 4)

The development of flat batter tanks has been taken a stage further by the development of the circular tank surrounded by a circular flat batter. This type of dam lends itself to construction with a dozer and/or scraper working in conjunction with a grader. The light-textured topsoil is removed and placed around the outer extremity of the flat batter in a wedge shape. The clay from lower in the excavation is then pushed out of the hole by the dozer, and is worked ever outwards by the grader moving in ever-increasing circles. This results in a thin clay blanket 5 to 15 cm thick, spread over the whole surface. The grade on the batter is about 1 percent.

A refinement that has been added to circular flat batter tanks is a raised wall around the lip of the excavation. The runoff from the flat batter collects in the trough on the outside of this wall. The gradient in the trough is so arranged that all the water flows to one point. At this point, it gains entry into the tank by means of a pipe

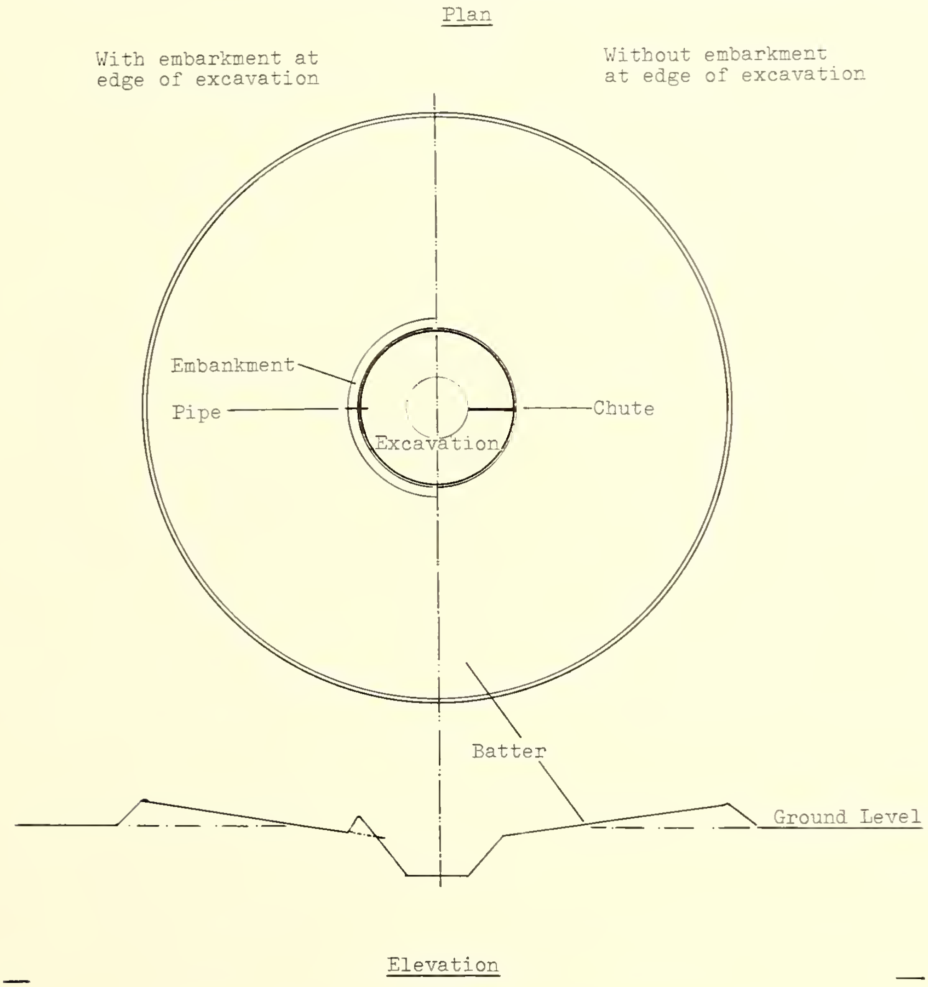
Plan
With embarkment at edge of excavation
Without embarkment at edge of excavation
Embankment
Pipe
Chute
Excavation
Batter
Ground Level
Elevation

FIGURE 4.--Circular flat batter tank.

or chute. This reduced the danger of erosion developing at the point of entry.

When a pipe is installed, by fitting a stopcock to it, appreciable aboveground storage can sometimes be gained. The cock is closed when the water level in the tank rises to inlet level. The tank is then topped up by pumping over the wall. However, sufficient clay is not always available to allow the wall to be raised much above the inlet level.

Circular flat batter tanks are being constructed with a radius of 100 m from the center of the excavation to the outer edge of the catchment--a total area of approximately 3.2 ha. With a tank of 5,000 m^3 excavated capacity, the area of the flat batter surface is approximately 3 ha. The largest flat batter tank built so far has an excavation of 1,500 m^3, a total area of approximately 8.5 ha and a batter area of 8.0 ha.

Runoff into the tank comes solely from the batters in the case of most circular and four-way push, flat batter tanks. In the case of three-way push tanks, natural catchment usually contributes some inflow in wetter years. Even with circular and four-way push tanks, it is sometimes possible to collect water from natural catchment or additional improved catchment, such as roaded catchment, and divert or pump it into the tank.

However, the amount of flat batter that can be obtained on a tank of given size and depth in any one situation is limited by the amount of clay available in the excavation. It is possible to augment the quantity of earth available by making a borrow pit around the perimeter of the catchment surface. Overburden can be dozed into the "wedge" in the early stages of construction to ensure adequate fall on the batters. This technique is used to maintain a maximum area of catchment on a sloping site.

Rollers are not normally used in the construction of flat batter catchments to achieve greater compaction. It is likely that some benefit would accrue in terms of improved runoff capability if the rollers were used. Whether this benefit would justify the extra cost of rolling is not known.

The flat batter dam is the standard water harvesting technique used in areas where the rainfall is greater than 400 mm and the depth of overburden covering the clay is 35 cm or more. The quality of flat batter catchments, in terms of ability to shed water, is generally considered to be comparable to good quality roaded catchment. Some farmers familiar with both, consider flat batter catchments to be superior.

One of the big advantages of the flat batter tank is that the catchment, being an integral part of the tank, takes up comparatively little "field room." This means that they can be used to take advantage of sites that lack sufficient size to accomodate a conventional tank and a roaded catchment. An example of their use in this regard is the siting of flat batter tanks in ridge tops in areas of low relief and high saline ground water levels. In these situations, the clay may be right to the surface of the original soil profile. Flat batter tanks do not have to be used solely in sites where the overburden is deep.

Their most serious disadvantage is that of limited size of catchment. This has so far restricted their use to the higher rainfall areas adjacent to the south coast. The capacity of the storage is large relative to the size of catchment; consequently, water level rarely reaches full supply level. However, in a water supply based on surface storage, the important thing is not that the tanks should always be full but, rather, that they should never be empty. Using this criterion, flat batter dams have performed well in practice.

Erosion, which has been a problem on square flat batter tanks, hopefully will be greatly reduced on the newer circular types in which the path of the inflowing water can be protected. On the square tanks, rilling commenced at the edge of the excavation where the water from the batter discharged into the tank. It was frequently severe at the corners where the water concentrated.

The flat batter tank idea has similarities with the "dew-pond" found on the chalk wolds of East Yorkshire, England, with which the author is familiar. These are relatively shallow, saucer-shaped, clay-lined ponds build on porous limestone. They frequently have no catchment other than that contained within the perimeter of the pond. Generally, they fill with dew. In addition, they accumulate snow in the winter, which drifts off surrounding arable land, and they collect the rain that falls on the batters at other times of the year. Very rarely were they brim full, but rarely were they empty. Many of them were constructed in the latter part of the 19th century and have since been rendered obsolete by reticulation.

Stripping the Topsoil

As a last resort, in situations where the tank is already constructed and experience has shown it to be deficient in catchment, the topsoil is removed to expose the clay subsoil. This is in situations where the depth of overburden covering the clay precludes the construction of roaded catchments in the normal manner.

A bulldozer is usually used to do the job--a crude operation, in which clay is exposed from the mouth of the tank back up the slope by pushing the topsoil into windrows. Occasionally, a grader is used subsequently to form roads; more often, the smooth, bare clay surface is the improved catchment.

Chemical Treatment

Asphalt or Bituminous Catchments

Sprayed asphalt pavements (6, 9, 14, 16) have been used for water harvesting by the PWD of Western Australia for at least 20 years to secure water supplies for towns. The construction and maintenance techniques used have been described by Kelsall. 9/ 10/ However, the known use of asphalt pavements on farms is restricted to five farms only. The main reason for this may well be that the advice on the subject available to farmers has been based on the experience of the PWD. Their standards, as Myers et al. (16) point out, are based on roadbuilding procedures and are expensive. The farm catchments that have been constructed have been built to less rigorous specifications.

The approach has been to remove the top 10 cm of soil to remove the bulk of the organic matter. The exposed surface has been leveled and compacted, a persistant weedicide applied, 11/ followed initially by a single coat of cutback bitumen emulsion. The first catchments put down in 1968 were subsequently resprayed with a second coat, and the catchment put down in 1973 is expected to be given a second coat in 1974.

9/ Kelsall, K. J. Construction of bituminous surfaces for water supply catchment areas in Western Australia. Pub. Works Dept., West. Austral. 13 pp. 1968. (Mimeographed.)

10/ Kelsall, K. J. Maintenance of bitumen catchment areas in Western Australia--Notes for guidance of field staff. Pub. Works Dept., West Austral. 11 pp. 1969. (Mimeographed.)

11/ The first catchments were not treated with weedicide and pasture, and weed seeds germinated through the bitumen.

Of the catchments put down so far, all but one have gone onto an in-situ lateritic gravel base. These have proved relatively durable. The exception had a base of fine grained sand. The bitumen film subsequently lifted from the sand and deteriorated beyond repair.

The performance of the first onfarm bitumen catchment was monitored through the winter of 1968. The results are given in table 1.

TABLE 1.—The percentage of runoff from 5 catchments: 3 roaded, 1 roaded and sprayed with chemical, and 1 bitumenized

	Area	Rainfall	Runoff	Runoff as 7/ percent of potential	Periods of records
	Hectares	Millimeters	Cubic meters	Percent	
Roaded catchments:					
Narrogin 1/	20.2	254	17,778	35	5/21 - 9/8/54
Dalwallinu 2/	40.2	169	5,948	9	Winter 1952
McAndrew's 3/	4.8	172	4,892	60	6/3 - 7/18/73
Roaded catchments + Petroset SB: 4/					
Sounness' 5/	1.15	201	839	41.5	5/5/ - 8/20/73
Bitumen:					
De Grossa's 6/	1.64	400	2,570	39	5/30 - 10/22/68

1/ Narrogin Town catchment; recorded by PWD of Western Australia (21).

2/ Dalwallinu Town catchment; recorded by PWD of Western Australia (21).

3/ McAndrew's farm catchment; Negus, T., Western Australia Department of Agriculture, Narrogin, private communication.

4/ Petroset SB - registered trade name of Phillips Petroleum Company, Oklahoma.

5/ Sounness' farm catchment; Feldman, J. R., Western Australia Department of Agriculture, Katanning, private communication.

6/ De Grossa's farm catchment; Burdass, W. J., unpublished data.

7/ No allowance was made for loss by seepage or evaporation for tanks (3/), (5/), and (6/). No allowance was made for drawoff for tank (6/). It is not known what losses, if any, were allowed for from tanks (1/) and (2/).

Fuel Oil (9)

This has been used on one 1/4-acre catchment where it was sprayed onto a coarse grained sand base. Details of its performance are not known.

Other Petroleum Products

A catchment was sprayed with the proprietary chemical Petroset SB 12/ in 1973.

The area of this catchment is approximately 1 ha. The ground was formed up as for a roaded catchment and sprayed with 1,000 liters of Petroset SB at a cost for material of $A1,100. The performance of this catchment for part of the winter of 1973 was monitored, and the results are given in table 1. In terms of runoff, the performance is fair, but erosion has occurred in the channels, and the life of the chemical treatment may prove disappointingly short.

DISCUSSION

Comparative Performance

There is a dearth of detailed information on the performance of onfarm water harvesting methods in Western Australia, and the information that is available (table 1) can at best only be described as "approximate." This dearth of information reflects the pragmatic approach and the important part played by farmers and earthmoving contractors in developing new ideas on water harvesting.

That the main methods used--contour drains, roaded catchments, and flat batters--are effective in the appropriate situation is vouched for by Soil Conservation Service personnel from their observations and experience. The fact that many farmers are using these methods and continue to expand their use speaks for itself.

The PWD of Western Australia has considerable experience in water harvesting. The rule of thumb used by their officers in predicting yields is 90 percent per inch of rainfall for bitumen, 45 percent from rock catchments, and 12.5 percent from roaded catchments. However, in their design work, they use the more conservative figure for bitumen of 56 percent of average rainfall to ensure adequate public supplies 9 years out of 10. They expect to impose restrictions on consumption 1 year in 10. 13/

Durability and Maintenance

Erosion of catchment surfaces and channels can be a problem and, with the broader catchment surfaces now being constructed, could well increase. The problem is closely related to the soil type. A complete covering of catchments with clay from the B horizon of some soils results in crust formation, which runs water readily, does not crumble, and is not a good host to vegetation.

Catchments constructed on self-mulching and well-structured soils do not form durable crusts. For this reason, snuffy morrel soils, red-brown earths, some of the red and brown podzols, and the solonized brown soils, in which there are numerous calcareous nodules, are to be avoided.

Clays associated with the "pallid zone" of the old lateritic peneplain produce some of the best shedding surfaces. These clays are often encountered in the deeper levels of flat batter tank excavations, and this may explain the superiority claimed for flat batters.

Pallid zone clays disperse in water because of the sodium present in the exchange complex. This property not only promotes crusting but

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12/ Registered trade name of Phillips Petroleum Company of Oklahoma.

13/ Private communication, PWD District Engineer, Water Supplies, Narrogin, Western Australia.

predisposes to erosion (9), (15). Erosion, sometimes serious, is common on catchment surfaces lined with pallid zone clays.

Catchments that do not crust, or that revegetate quickly, benefit from regular maintenance. In one instance, where subsequent performance was monitored following grading and rolling, runoff fell from 43 percent of potential, in the year maintenance was carried out, to 15 percent in the second, to 12 percent in the third. 14/

Farm catchments deteriorate because of surface weathering and erosion, growth of vegetation, and trampling of livestock. It is advisable to exclude stock from treated surfaces; not only do they trample on the surface, but their dung washes into the tank and pollutes the water. In practice, stock are excluded from all bitumen catchments, some flat-batters, but very few roaded catchments. The maintenance of farm catchment surfaces is carried out intermittently, tending to be done in the year after the drought rather than as a regular operation.

Costs

Hollick (10) gives comparative catchment costs for a range of surface treatments, allowing for both capital and maintenance costs in his analysis. His conclusion is that of the surface treatments the roaded catchment is the cheapest. He calculates that 1,000 liters of runoff harvested from bitumen cost 4.4 times as much as from roading. He does not include figures for flat batters in his analysis.

The dearth of reliable yield data for onfarm water harvesting methods in Western Australia makes it difficult to produce meaningful comparative costs on the basis of "unit of water" harvested.

Contour drains are most often built by the farmer using his own equipment. Other work is done by earthmoving contractors, of which there are a considerable number. The majority of these are in a small way of business, operating one, two, or three machines only. Their usual equipment consists of one or two tracked tractors in the horsepower range 125 to 383 (at the flywheel), fitted with dozer blade and mounted ripper, and a small boring unit for test boring tank sites. A few contractors also operate a grader in the horsepower range 125 to 150 (at the flywheel). Very few operate special compacting equipment.

The narrow range of equipment generally available through the local contractors does limit the mode of construction and even the type of structure that can be built. The better compaction that could be achieved by the use of rollers would probably improve the ability of most surfaces to shed water. However, whether the extra water so gained would justify the extra cost must be questioned. The cost of excavation work is normally quoted at so much per cubic meter, that for catchment formation at so much per hour. A range of construction costs is given in the Appendix.

CONCLUSION

Water harvesting on farms in Western Australia has been practiced for many years. The level of activity is subject to fluctuations related to economic circumstances and recent experience of the climatic cycle.

A series of drier years commenced in 1969 and demonstrated that water supplies on many farms were inadequate for the stock being carried. In the summer of 1969-70, for example, 21 percent of farmers surveyed carted water to their stock from offfarm sources. 15/

14/ See footnote 13.

15/ See footnote 3.

This widespread water shortage stimulated the farmers into upgrading old facilities and constructing new ones. As a result, there has been a considerable increase in the number of contour drains and roaded catchments on the farms--some of these built to the design of Frith and Nulsen (7)--and a lesser increase in the number of flat batter tanks since 1969. The water shortage also stimulated the Soil Conservation Service into examining the efficacy of old techniques and investigating the possibilities of new ones.

In addition, experimental work has been initiated by Laing 16/ and Hollick 17/, and ideas such as Marsh's miniroad theory 18/ have been put forward but have not been fully explored.

For the foreseeable future, the roaded catchment is likely to remain the standard surface treatment for water harvesting on farms in Western Australia. Flat batter tanks will be used where a comparable amount of catchment and storage can be built more cheaply than can be gained using roaded catchment and a conventional tank 19/ or where the limited area of the site precluded the use of a roaded catchment. The very wide "jumbo" sized roaded catchments (20 m wide crest to crest) will not find common use because of their high cost and the problem of erosion in their broad, steep surfaces.

Bitumen will find limited use in situations where other methods are not technically feasible and where gravel suitable as a base for bitumen is found in situ. Bitumen catchments are an ideal Christmas present for the farmer's wife who has everything but a good farmhouse water supply.

On many farms, saline underground water is available at moderate depth. In the more distant future, should a cheap, compact, easily operated desalination plant come onto the market, it is possible that water harvesting on farms in Wester Australia could be phased out.

ACKNOWLEDGMENTS

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16/ See footnote 2.

17/ See footnotes 5 and 8.

18/ Marsh, B. a 'B. Mini roads. West. Austral. Dept. Agr., 3 pp. 1972. (Mimeographed.)

19/ When the cost of roaded catchment rises to the value given by

$$RC = \frac{V\ (xf - xc)}{a}$$

where RC = cost of roaded catchment
V = volume of excavation in cubic meters
xf = cost of excavating flat batter tanks in dollars per cubic meter
xc = cost of excavating a conventional tank in dollars per cubic meter
a = area in hectares

it will be as cheap to construct a flat batter tank as to construct a combination of conventional tank plus a roaded catchment. This assumes that the size of excavation and of catchment are the same in both systems.

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APPENDIX

Cost of constructing water harvesting structures on farms, as of January 25, 1974

	Low	High
Conventional excavated tank per cubic meter	$0.30	$0.34
Flat batter tank and catchment 1/ per cubic meter	.46	.52
Roaded catchment 2/ per hectare	100.00	300.00
Roaded catchment jumbo size 3/ per hectare	450.00	500.00
Grade banks 4/, disk plow built per kilometer	5.00	10.00
Grade banks 5/, grader built per kilometer	8.00	22.00
Bitumen catchment per hectare:		
Site preparation 6/	300.00	400.00
Residual herbicide	70.00	120.00
Bitumen emulsion 7/ (1 coat applied)	1040.00	1140.00
Fencing	130.00	150.00
	$1540.00	$1810.00

1/ The tank and catchment are quoted for as a unit. Cost increases with the width of catchment, that is, the distance that the earth has to be moved.

2/ Cost increases as the width of road increases, and is also related to the hardness of the clay. Hard clay has to be ripped.

3/ Built to the specifications suggested by Frith and Nulsen (7) with a depth to clay of about 0.5 m. It includes the cost of rolling. If the depth of cut doubles, the quantity of earth to be moved increases fourfold. Costs go up likewise.

4/ Low cost banks built using a large plow in flat wheatbelt country with no obstructions; high cost banks built with small plow in steep hilly country with many obstructions.

5/ Low cost = wheatbelt; high cost = steep hilly country.

6/ Leveling with a grader followed by compaction with a roller.

7/ Cost increases with distance from refinery; economics of scale reduce the cost.

ENGINEERING ASPECTS OF WATER HARVESTING RESEARCH AT THE UNIVERSITY OF ARIZONA [1]

C. Brent Cluff [2]

INTRODUCTION

Water harvesting research at the University of Arizona intensified in the early 1960's. In that period, the following facilities were installed at the Water Resources Research Center Field Laboratory: (1) A series of 8-by 16-foot plots for testing impervious land treatments for collection of precipitation, (2) three lined reservoirs for testing evaporation control material, and (3) double ring infiltrometers for testing seepage control methods. These facilities have been used to test materials suitable for a water harvesting system. The system includes the catchment and storage. The better systems have been tested on a larger scale at various other locations throughout Arizona.

This paper will discuss in detail the engineering aspects of the specific systems that have warranted larger scale testing at the University of Arizona. These water harvesting systems were developed in order to (1) provide a dependable supply of water for wildlife and stock purposes, (2) provide a high-quality water for domestic and industrial supplies, and (3) extend agriculture into lands presently uncultivated due to lack of water.

CATCHMENTS

Research at the University of Arizona has indicated that no one method of land treatment is superior at all sites. Each site needs to be analyzed to determine the optimum method. Based on the results of small plot tests, on the experience of other researchers, and on economics, larger scale testing at the University of Arizona has been made with the following treatments: (1) compacted earth (CE), (2) compacted earth sodium treated (CEST), (3) gravel covered plastic (GCP), and (4) asphalt-plastic-asphalt-chipcoated (APAC).

Compacted Earth (CE)

This type of catchment is the University of Arizona's version of the "roaded catchment," which was initiated in Australia in 1948 (2).

A 1-acre CE catchment was constructed in the spring of 1970 at Atterbury Experimental Watershed located east of Tucson. The textural analysis of soils at this site is given in table 1. The soil is easily compacted but also contains sufficient sand and gravel to inhibit erosion. Two 300-foot-long drains, spaced 50 feet apart, collected water from 25-foot-long slopes. The side slopes of the drainage channels varied

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[1] The research upon which this report is based was funded by the State of Arizona and the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964.

[2] Associate hydrologist, Water Resources Research Center, University of Arizona, Tucson.

from 3 to 10 percent. The drainage channels were covered with plastic and gravel to prevent both erosion and water loss. After a 1/2-inch rainfall, the catchment was shaped with a road grader and smoothed with a tractor-drawn rotary rock rake (6). The rainfall provided the soil moisture necessary for optimum grading. The rock rake saved considerable time and left a smoother surface than possible with a grader. After an additional one-half inch of precipitation, the plot was compacted with a 26-ton vibratory drum roller. The drainage channels were also lined at this time. The total cost of the 1-acre catchment was approximately $300, including equipment rental and labor. 3/ The cost is dependent on (1) site accessibility, (2) soil type, (3) type of terrain, and (4) type of native vegetation. On larger catchments, or when several catchments are built at one time, the cost under conditions similar to those in the Tucson area would be substantially less than $300 per acre.

The catchment is located in desert shrub vegetation and has required only minimum weed and shrub control since it was installed 4 years ago. During an 18-month period following installation, a total rainfall of 19.73 inches occurred. The CE plot yielded 6.96 inches or approximately 35 percent of the total rainfall, whereas the control plot yielded only 4.86 inches.

Compacted Earth Sodium Treated (CEST)

Previous research (6, 12) indicated that small amounts of sodium, when applied to the surface of desert soils where there is little or no vegetation, will cause a dramatic but somewhat temporary reduction in infiltration rate.

More effective results have been obtained when the sodium chloride treatment is coupled with clearing, shaping, and compaction as described above. The sodium not only reduces the permeability of the soil but also serves as a herbicide, which will greatly reduce the cost of weed control at many locations.

A CEST catchment has been field tested on an acre site at Page Experimental Ranch about 20 miles north of Tucson. An analysis of the surface soil is given in table 1. The catchment was prepared in the spring of 1971 in the same way as the CE catchment. The only difference is that the plot was rototilled to destroy soil structure in the upper 2 inches. Five tons of granulated sodium salt was then added with a fertilizer spreader. The granulated salt was mixed into the upper 1 to 2 inches, and the soil surface smoothed with the rotating tractor-drawn rock rake (see fig. 1). After a 4/10-inch rainfall, the catchment was compacted with a drum roller. The total cost of this catchment was approximately $500. Economy in scale should reduce this cost more than 30 percent.

Grapes and deciduous fruit trees have been planted in the drainage ways making this a dual purpose catchment. Excess water is stored in a salt-treated storage tank (6). The agricultural aspects of this system are described in a separate symposium report by Dutt and McCreary (9). The efficiency of the catchment, excluding the runoff water used by the plants in the drainage ways, has been greater than 50 percent. Rainfall infiltrometer tests (7) as well as multipeak hydrograph analysis (16) have indicated that the terminal infiltration rate on the catchment is close to zero. Figure 2 shows the effect of the sodium chloride in controlling weeds and growth of trees. A CE catchment would have been impractical at this site.

3/ All cost estimates presented in this paper are in U.S. dollars and are based on 1974 costs and methods of construction in Arizona.

TABLE 1.--Soil characteristics of selected catchment sites

Location	Soil texture			Soil Classification
	Sand	Silt	Clay	
	Percent	Percent	Percent	
Atterbury Experimental Watershed CE catchment (H-5)	72	17	11	Sandy loam.
Page Experimental Ranch CEST catchment	45	33	22	Loam.
Papago Reservation near San Vicinte Papago 1 catchment	70	26	4	Sandy loam.

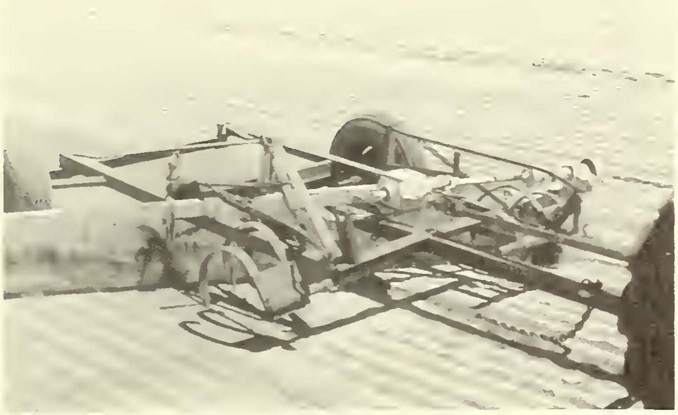

FIGURE 1.--Rotary rock rake used in the construction of the compacted earth (CE) and compacted earth sodium treated (CEST) catchments.

In the spring of 1973, a 3/4-acre gravel covered plastic catchment was installed on the Papago Reservation west of Tucson. This treatment was selected after the soil analysis, as given in table 1, indicated the site was somewhat deficient in clay and therefore probably not suitable for a CEST catchment. Since the area contained considerable grass and annuals, it was to be treated with sodium chloride prior to covering with plastic and gravel. The plot was prepared in the same way as the CEST catchment. An unexpected low intensity rainfall of approximately one-tenth inch per hour occurred during the morning the gravel covered plastic cover was to be installed. This provided the opportunity to demonstrate the effect of compaction on a sodium treated plot. A pickup truck was rolled back and forth over the plot for compaction, which resulted in the runoff shown in figure 3. The uncompacted sodium-treated area, as well as a compacted but otherwise untreated road in the area, did not

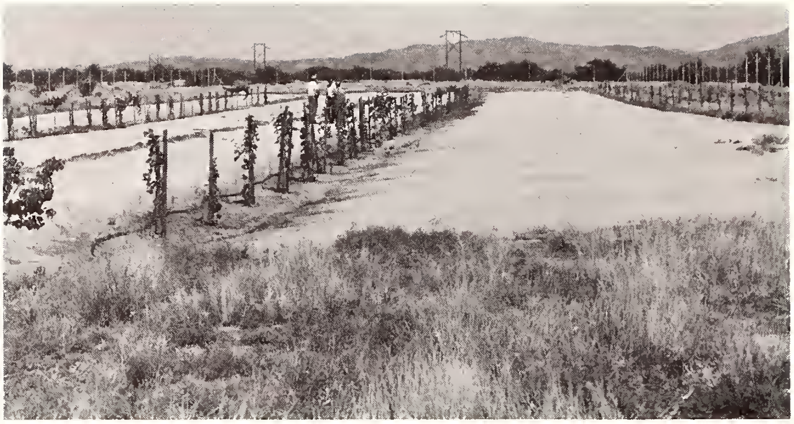

FIGURE 2.--Multipurpose compacted earth sodium treated (CEST) catchment at Page Experimental Ranch. Note the absence of grass in the area treated with sodium chloride.

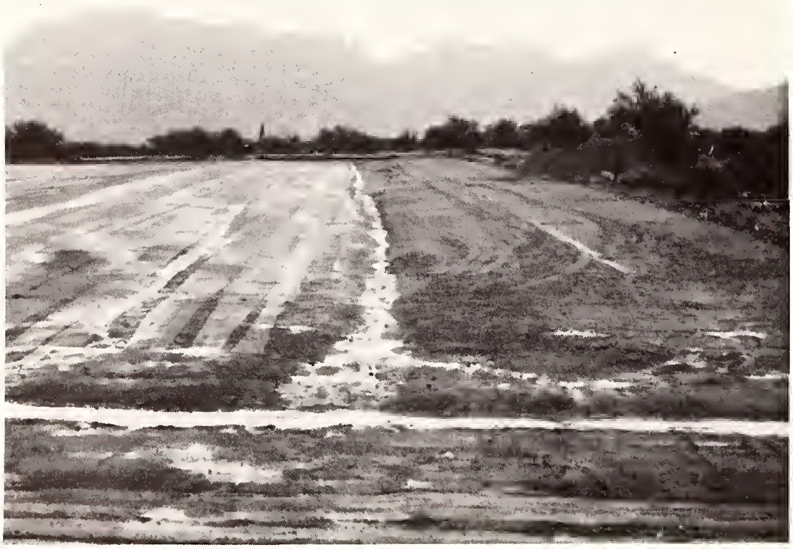

FIGURE 3.--Compacted sodium treated on the left, sodium treated but uncompacted on the right during a 1/10 in/h rainfall.

shed water. Thus, figure 3 graphically illustrates the importance of compaction and the potential of the CEST catchment even in areas where the soil contains relatively small amounts of clay.

Gravel Covered Plastic (GCP)

A gravel cover protects inexpensive plastic sheeting from ultraviolet induced oxidation and wind damage. A gravel-sovered plastic catchment was first installed at the Water Resources Research Center Field Laboratory in December of 1965. The 6-mil polyethylene plastic used in the first installation is, after approximately 9 years, in excellent condition. The efficiency 4/ of the plot has averaged 70 percent or approximately 230,000 gal/acre/yr.

4/ Efficiency is the percentage of the total rainfall collected on the catchment.

Where gravel is imported, gravel-covered plastic catchments have been installed, using a plastic-laying gravel chute, which fits on the back of a dump truck (3) and a self-propelled chip spreader equipped with a plastic dispenser. The 3/4-acre graveled plastic catchment on the Papago Reservation, discussed in the preceding section, was installed with the modified spreader (see fig. 4).

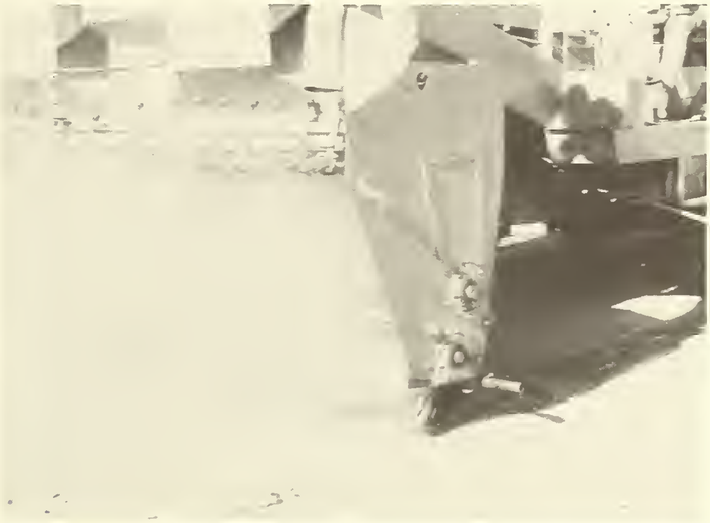

FIGURE 4.--Installing a gravel-covered plastic (GCP) catchment with a modified self-propelled chip spreader.

Where specialized equipment is not available or if the catchment is too small to justify its use, a front end loader and hand labor can be used. In the spring of 1971, two 12,000 ft^2 GCP catchments were installed in cooperation with the U.S. Bureau of Land Management (14) near Safford, Ariz., at an approximate rate of 2,000 ft^2/h with a 3/4-yd^3 tractor loader and a crew of five.

Many areas of the world have sufficient gravel in the soil profile that importation of gravel is not needed to cover plastic. As a demonstration of this, a 2,000-ft^2 catchment was constructed with gravel hand screened from the soil profile at a cost of $32 worth of plastic and 44 hours of labor.

A machine, developed at the University of Arizona, extracts gravel from the soil, dispenses plastic, and covers the plastic with the extracted rock (3). Although improvements are needed, tests using the machine, referred to as the gravel extracting soil sifter (GESS), have shown the advantages in this type of automated installation where there is sufficient gravel in the soil profile.

The amount of water harvested with a GCP catchment, is dependent on the depth and type of gravel cover and total rainfall received in each storm. The depth and type of gravel control the amount of water trapped on the catchment during each storm. In properly constructed GCP catchments, this loss per storm has been found to vary from 0.06 to 0.11 inches. The rate of loss increases with time until the gravel cover is fully saturated with dust. This loss will be minimized if the plastic is covered with the smallest size and depth of gravel needed to provide a complete cover and resist erosion. This loss can be estimated from figure 5. This figure shows that on a 10-percent slope, 100 feet

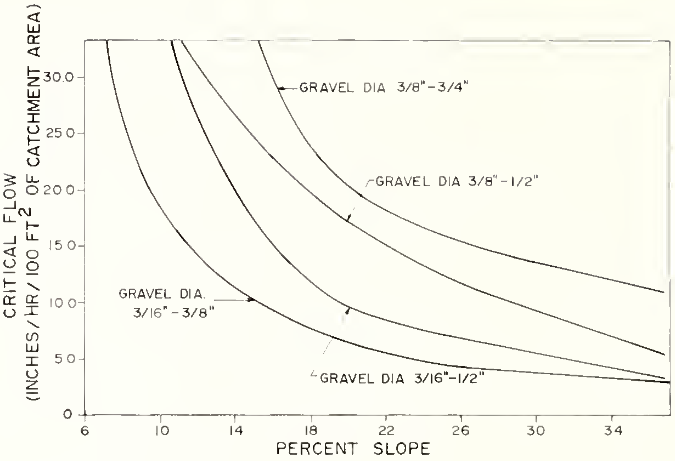

FIGURE 5.--Critical flow versus percent slope for selected sizes of gravel cover.

long, a 1/2-inch cover of 3/16- to 3/8-inch gravel will withstand an 18 in/h intensity rainfall. The ideal gradation of gravel is that which will maximize the density of the cover. This gradation can be determined from Fuller's maximum density curve (11):

$$P = \sqrt{dD}$$

where P = percentage passing screen size d

d = passing screen size

D = maximum particle diameter

Maintenance of a GCP catchment consists of covering exposed plastic, preferably from stockpiles left for that purpose at the time of construction. In contrast with other type treatments, the maintenance of a properly constructed, gravel-covered catchment will decrease with time as the gravel tends to reorient and settle with each succeeding rain that is of higher intensity than the preceding one.

Various types of aggregate can be used for a cover. In Jamaica, a 1,800 yd^2 GCP catchment has been constructed with limestone chips (15). Volcanic cinders have also been used (7). Other impermeable membranes, such as roofing felt, have also been used under a gravel cover (9).

In contrast with the CE and CEST catchments, the GCP catchment produces sediment-free water. The cost depends on the cost of the gravel and method of installation. A range of $1,200 to $2,900 per acre has been projected based on experience in constructing several GCP catchments over the past 9 years.

Asphalt-Plastic-Asphalt-Chipcoated (APAC)

This treatment consists of applying a tack coat of emulsified asphalt, and then laying down polyethylene matting or polyethylene sheeting. Asphalt is then sprayed on top of the plastic, which is immediately coated with 1/8- to 3/8-inch chips. Four 8- by 16-foot plots, which use this type of treatment, were installed beginning in 1971. The efficiency has been in excess of 95 percent. The gravel requirement of 20 to 30 lb/yd^2 for this type of catchment is approximately one-third of that required for gravel covered plastic catchments.

The above installations indicated that 4-mil polyethylene sheeting was superior to heavier thicknesses of plastic. (The heavier plastic exhibits independent characteristics and does not form an integral membrane.) The polypropylene matting proved to be more compatible with the asphalt than the polyethylene when application was made at temperatures below 100° F. At higher temperatures, the bond between the asphalt and polyethylene is improved.

Two 1/2-acre APAC catchments were installed on the Papago Indian Reservation in the spring of 1973 using a 1,200-gal asphalt dispensing truck and an 8 yd^3 dump truck equipped with a chip spreader. The two sites were prepared in the same manner as CEST catchments with the sodium chloride treatments being used as a herbicide. Polypropylene matting [5] was used on one catchment, whereas 24-by 100-foot rolls of 4-mil black polyethylene was used as reinforcement on the other. The emulsified asphalt was heated to 140° F prior to application. The plastic was unrolled by hand after application of the prime coat of asphalt. A garden roller was used to tack the plastic to the prime coat prior to the application of the chips. A pickup was then driven back and forth on the plastic. After the plastic was installed, a layer of asphalt and chips was applied, which completed the treatment.

The APAC covering was installed at an approximate rate of 5,000 ft^2/h with a crew of nine. [6] The costs of preparing and treating the site with polyethylene was estimated at $1,800, including a $600 transportation cost from Tucson to the site (5). The most time-consuming part of the APAC treatment, unrolling the plastic, can be automated. With this improvement and an experienced crew, it should be possible to double the rate of installation and reduce the costs accordingly.

There was not much difference between the two materials as far as ease in installation. The polyethylene wrinkled less than the polypropylene.

WATER STORAGE

Evaporation and seepage control are needed in order to successfully store water collected from a water harvesting catchment. The methods used in achieving this control are somewhat dependent on the size and function of the reservoir. The following discussion primarily concerns techniques suitable for small tanks; however, some of the methods of seepage and evaporation control could also be used on larger reservoirs.

Plastic-Lined, Rock-Filled Tanks

The use of a plastic-lined, rock-filled tank was prompted by the availability of commercial rock pickers, which makes the collection of rock for small tanks economical. The rock decreases available storage space by over 50 percent but greatly reduces evaporation loss, damage by animals, and the possibility of vandalism. The tank requires a sediment-free source of water, such as that provided by GCP or APAC catchment.

The tank is first excavated, then the surface is raked smooth. Two or three layers of 10-mil polyethylene are then laid down and covered with used rubber tires. The tires are filled with silty clay cover material to anchor the tires and to reduce the seepage through any holes that may occur in the plastic. The tires protect the plastic as rocks are added to the tank. In the United States, used rubber tires can easily be obtained at little or no cost. Where tires are difficult to obtain, a wire mesh reinforced coat of cement mortar or a 12-to 18-inch layer of soil could be used to protect the plastic.

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[5] The polypropylene matting was furnished by EXXON.

[6] The crew included 5 Papago High School students.

Three rock-filled tanks have been constructed in Arizona using a rotary drum commercial rock picker. A cost analysis made on one of the 25,000-gal [7] tanks constructed at Safford indicated a $700 cost for excavation and placement of the plastic and tires and $1,600 cost for filling the tank with rock, a total of $2,300 (6).

The rock-filled tank is very compatible with the GCP catchment. The larger rock can go into the tank with the smaller rock being used on the catchment. A limestone rock-filled tank, patterned after the Arizona tanks, has also been constructed in Jamaica to collect water from a fiber glass reinforced asphalt catchment (14). The rock in the Jamaica tank was collected by hand.

Plastic-Lined Mortar-Coated Tanks

Plastic lining, if properly covered, offers a positive method of seepage control that is very competitive with other methods. A cover not only will protect the liner from mechanical damage but will minimize the effect of any holes inadvertantly placed during construction (1). Soil can be used effectively as a cover for plastic in the bottom of ponds, but is not suitable for the steep slopes generally preferred in small reservoirs.

A coating of wire-reinforced cement mortar placed directly on a polyethylene plastic lining has proven to be an effective cover to use on steep slopes. This coating may be placed with gunnite equipment or can be plastered on by hand. The cost of this protective cover is dependent of the method of installation but has averaged less than 20 cents/ft^2. A tank, with a covering of soil in the bottom and reinforced mortar on the sides, is shown in figure 6. The economy and strength of the reinforced mortar-covered plastic can also be used to construct a walk-through cattle trough that is directly connected to the tank. Such a design avoids the need for a float valve, which is subject to malfunction and vandalism. A 100,000 gal tank, of the type depicted in figure 6, was constructed on the Papago Indian Reservation at one of the sites of the APAC catchments described earlier. A double layer of 10-mil black polyethylene plastic was used. The plastic was covered in the bottom with soil and on the sides with hand plastered wire-reinforced mortar. A cost estimate of the tank is given in table 2.

Evaporation control was obtained through use of the coupled-expanded-polystyrene-asphalt-chipcoated (CEPAC) raft first tested at the University of Arizona in the spring of 1972 (4). Four-by four-foot sheets of expanded polystyrene, 1 inch thick, are coated with emulsified asphalt and covered with a layer of 1/16-to 1/8-inch chips. They are then coupled together with a coupler made out of two short lengths of slotted, 1-1/2-inch PVC pipe. An outer frame of 1-1/4-inch PVC pipe provides a protective bumper for the rafts. The rafts have been constructed up to 1,600 ft^2. These 1,600 ft^2 rafts can be coupled together to cover as large a body of water as desired.

This relatively inexpensive method of evaporation control makes it practical to build shallow tanks. This is important in areas of limited soil depth or where excavation is difficult. The shallow tank also makes the walk-through trough practical.

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[7] Total capacity before filling with rock was approximately 50,000 gal.

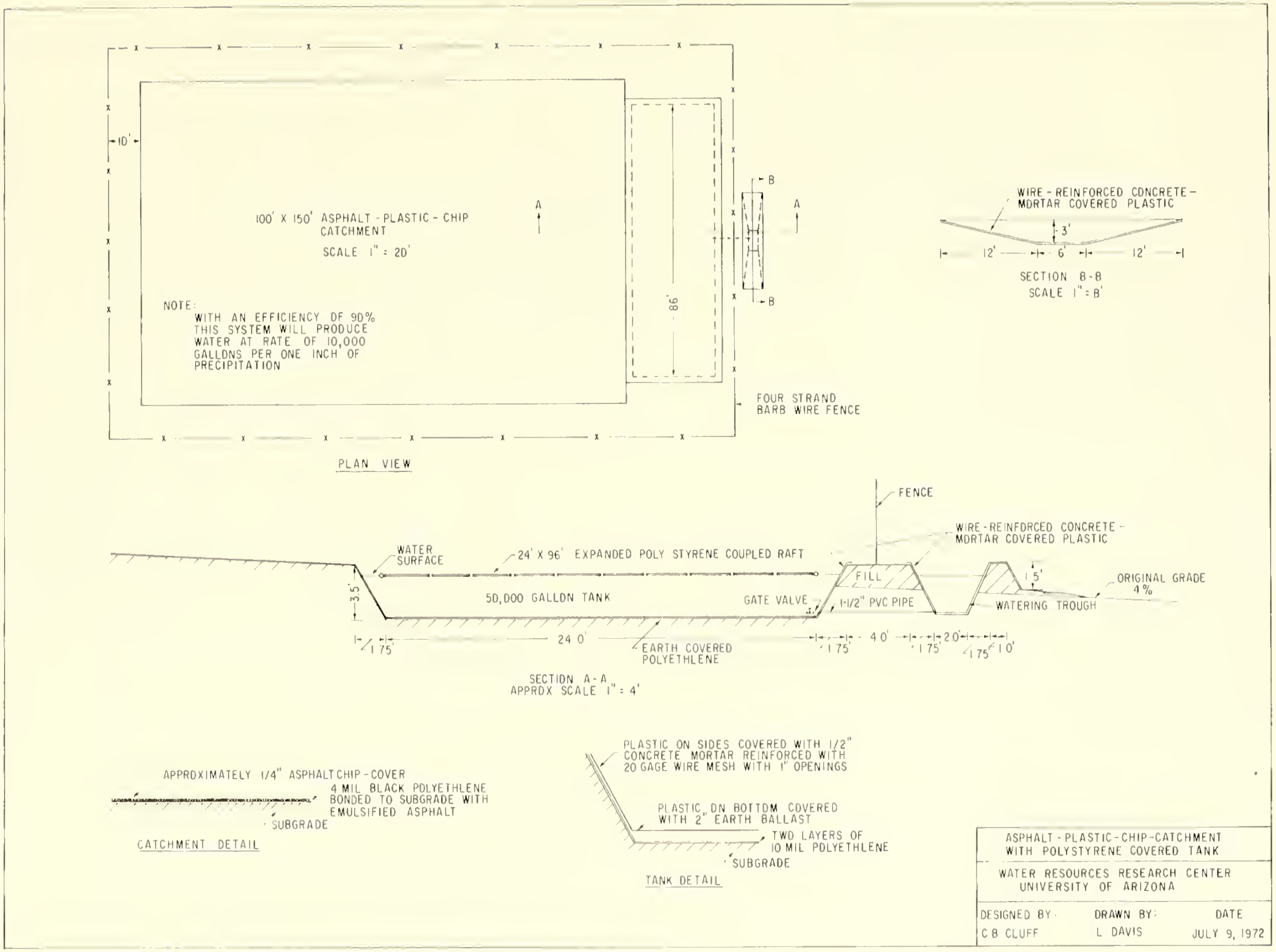
100' X 150' ASPHALT - PLASTIC - CHIP CATCHMENT
SCALE 1" = 20'
NOTE:
WITH AN EFFICIENCY OF 90% THIS SYSTEM WILL PRODUCE WATER AT RATE OF 10,000 GALLONS PER ONE INCH OF PRECIPITATION
10'
A
B
98'
FOUR STRAND BARB WIRE FENCE
PLAN VIEW
WIRE - REINFORCED CONCRETE - MORTAR COVERED PLASTIC
3'
12'
6'
12'
SECTION B-B
SCALE 1" = 8'
FENCE
WIRE - REINFORCED CONCRETE - MORTAR COVERED PLASTIC
WATER SURFACE
24' X 96' EXPANDED POLY STYRENE COUPLED RAFT
FILL
1.5'
ORIGINAL GRADE 4%
3.5'
50,000 GALLON TANK
GATE VALVE
1-1/2" PVC PIPE
WATERING TROUGH
1.75'
24.0'
EARTH COVERED POLYETHLENE
1.75'
4.0'
1.75'
2.0'
1.75'
1.0'
SECTION A-A
APPROX SCALE 1" = 4'
APPROXIMATELY 1/4" ASPHALTCHIP - COVER
4 MIL BLACK POLYETHLENE BONDED TO SUBGRADE WITH EMULSIFIED ASPHALT
SUBGRADE
CATCHMENT DETAIL
PLASTIC ON SIDES COVERED WITH 1/2" CONCRETE MORTAR REINFORCED WITH 20 GAGE WIRE MESH WITH 1" OPENINGS
PLASTIC ON BOTTOM COVERED WITH 2" EARTH BALLAST
TWO LAYERS OF 10 MIL POLYETHLENE
SUBGRADE
TANK DETAIL
ASPHALT - PLASTIC - CHIP - CATCHMENT WITH POLYSTYRENE COVERED TANK
WATER RESOURCES RESEARCH CENTER UNIVERSITY OF ARIZONA
DESIGNED BY: C B CLUFF
DRAWN BY: L DAVIS
DATE JULY 9, 1972

FIGURE 6.--Asphalt-plastic-chip-catchment with polystyrene-covered tank.

TABLE 2.--Cost analysis[1] of 100,000-gallon storage tank and trough at Papago 2 water harvesting system

Excavation:			
Equipment rental: (with operator)			
International TD 24 dozer	2 h	@ $22	$ 44
Case 450 dozer	8 h	@ $15	120
Layout and supervision	5 h	@ $ 8	40
Hand labor	8 h	@ $ 3	24
			$228
Lining:			
Equipment rental:			
Loader	2 days	@ $80	160
1/2 yd^3 cement mixer (hopper loaded)	1 day	@ $40	40
Materials: 3/			
Polyethylene (10 mil black)	8,000 ft^2	@ $0.015	120
Wire mesh (1-inch opening-20 gage galvanized)	2,500 ft^2	@ $0.034	85
Cement	80 sacks	@ $1.60	128
Labor	140 h	@ $3	420
			$953
Evaporation cover:			
CEPAC raft	1,400 ft^2	@ $0.15 2/	210
Total			$1,391

1/ The cost analysis does not include transportation costs from Tucson to the site.

2/ Includes installation.

3/ The earth cover and sand for the cement were obtained near the site, using the loader.

Sodium-Treated Tank

When there is sufficient clay in the soil and the incoming water is of low salinity but higher in sodium than calcium plus magnesium, then the use of sodium salt is generally the most economical method of seepage control. This type of tank is particularly compatible for collecting water from a sodium-treated catchment. This was demonstrated in connection with the salt-treated catchment at Page Experimental Ranch (6, 9). The seepage loss at this tank appears to be insignificant. The life of the sodium treatment seal should be indefinite, due to the fact that the incoming water has a higher sodium content than calcium plus magnesium. Evaporation has been successfully controlled at Page Experimental Ranch for approximately 2 years with a CEPAC raft cover.

DISCUSSION AND CONCLUSIONS

A summary of projected costs and the estimated life of the catchments tested at the University of Arizona is given in table 3.

TABLE 3.--Relative cost and efficiency of catchments tested at the University of Arizona, January 1974

Catchment methods	Approx. cost per acre	Efficiency	Estimated Life
	Dollars	Percent	
Compacted earth (CE) 1/	180-300	30-60	Indefinite.
Compacted earth sodium treated (CEST) 1/	360-600	40-70	Indefinite.
Graveled plastic (GCP) 2/	1,200-2,900	60-80	20-25 years.
Asphalt-plastic Asphalt-chip-coated (APAC) 3/			
Polyethylene reinforced	2,000-2,900	85-95	10-15 years.
Polypropylene reinforced	3,700-4,600	85-95	10-15 years.

1/ Prices and efficiency of CE and CEST catchments are dependent on soil type, cost of clearing, and shaping. Maintenance consists of weed removal and recompaction as needed. Additional NaCl may be required periodically prior to recompaction for maintenance of the CEST catchment.

2/ The variation in price of the GCP catchment is primarily dependent on the cost of the gravel and, to a lesser extent, the cost of clearing and shaping. Maintenance consists of adding gravel at required on exposed portions of the catchment. At the end of 20 to 25 years the plastic may need to be replaced. The gravel, however, can be reused indefinitely.

3/ Prices of the APAC systems are based on projections from 1/2-acre plots assuming automated installation of plastic. Maintenance consists of recoating with asphalt and chips every 10 to 25 years at a cost of less than one-third the original cost of the catchment. This estimated life is based on experience from similar types of treatments in the roofing industry.

The CE and CEST catchments are soil dependent. These catchments should not be built where soils are difficult to compact. More tests are needed to determine suitability, but, in general, clay content should not be less than 5 nor greater than 35 percent. For soils with higher clay content, it would be important to have more sand and gravel than silt in order to avoid erosion problems.

Water produced from a CE or CEST catchment contains considerable sediment, which should be removed before being used for domestic purposes. Water from a CEST catchment will have a higher sodium and chloride content than a CE system, but the total salinity will be less than 500 parts per million and can be used for most purposes including agriculture (6).

Sodium-treated tanks in general should work well in conditions favoring the CE or CEST catchment. The tank should be constructed with a sediment trap or in such a way that the tank could be periodically cleaned out.

A GCP catchment should be considered if the soil conditions are not suitable for a CE or CEST treatment and gravel is economically available and/or a sediment-free water is desired.

The rock-filled tank is recommended to store sediment-free water where sufficient rock is available and vandalism is a problem. Otherwise, an earth and reinforced mortar-covered plastic-lined tank with a CEPAC cover is recommended.

The APAC system would be used in areas where (1) soil or gravel conditions are such to make the CE, CEST, or GCP impractical and/or (2) rainfall and/or storage considerations are such that a high efficiency would be needed to maintain a firm water supply. In general, the same type of storage system used for the GCP catchment could be used for the APAC system. The size of the storage could be reduced due to the higher efficiency of the APAC system.

Other systems of catchment and storage construction, as discussed in this symposium, may have particular advantage at a given site. It is important to evaluate each site to determine the best system to use.

Although more research is needed, costs of installing water harvesting systems have been greatly reduced by applying modern methods and techniques. Water harvesting systems should be considered whenever new water supplies for domestic and livestock use in developing arid and semiarid lands are needed. If the cost is low enough or the value of the crop is high enough, the water harvesting systems described in this paper can also be used to develop new agricultural lands where water is presently unavailable.

ACKNOWLEDGMENTS

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WATER HARVESTING FOR LIVESTOCK, WILDLIFE, AND DOMESTIC USE

Gary Frasier [1]

INTRODUCTION

Our vast rangelands can be used for maximum benefit only when a uniformly distributed and adequate water supply is available. Many rangeland areas are overgrazed around present water sources, whereas large portions of the land and forage are unused because of inadequate stock water. Many of our rural farms from the Midwest to the Far West do not have adequate supplies of good water for household use. This forces our farmers and ranchers to use their time, energy, and money to import water by hauling or piping long distances (6). Water harvesting can frequently supply this badly needed water without adding to the energy shortage or polluting our environment. As an added benefit, many of the water harvesting techniques can supply the necessary quantities of water at less cost than other more "conventional" means.

One of the earliest water harvesting systems used in the United States was the collection of rainwater from the roofs of houses. Although seldom used today, this method is a potential low-cost system for supplementing water supplies. The water collection apron, the roof of the house, is already in place. All that is needed is additional gutters and a suitable water storage system. While this system will probably not supply all the water desired for a modern household, with automatic washing machines and two bathrooms, it can be used to obtain good quality water, which might not otherwise be available.

Water for livestock and wildlife on our rangelands can often be similarly obtained. Areas of "slickrock" can provide large quantities of water during rainstorms. Also, crossing the grazing areas of this country are thousands of miles of paved highways usually designed so water will run off. If this water can be collected, we have a potential low-cost water harvesting system. Should none of these "natural" systems be available, we can still harvest the precipitation by constructing "artificial" catchments. These structures do require time and money to install, but, when properly designed and constructed, they can provide water where needed at less cost than other methods.

CATCHMENT EFFICIENCY

Many factors must be considered in designing a satisfactory water harvesting system. Some items, such as the distribution and quantities of the required water, are easily estimated. Other factors, like precipitation quantities and distribution, require careful selection and judicious use. The runoff efficiency of various catchment treatments is difficult to generalize. The efficiency, usually expressed as a percentage of the precipitation as measured by a rain gage, depends on factors such as antecedent soil moisture, storm intensity, and storm duration. Materials such as artificial rubber or sheet metal are usually assumed to yield 100 percent average runoff. Other types of treatments often yield less than 100 percent.

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One factor usually not considered when selecting the type of water harvesting catchment is the minimum or threshold quantity of precipitation required to produce runoff. Figure 1 shows a plot of rainfall vs. runoff by storm events for a treatment that does not have 100 percent runoff. The best fit line of the form

$$y = A + Bx \qquad (1)$$

where

y = runoff in millimeters

A = intercept of best fit line

B = slope of best fit line

x = precipitation in millimeters

was computed for the data by least squares techniques. For the runoff, y, set equal to zero,

$$x = -A/B \qquad (2)$$

This value of x is equal to the threshold rainfall, and B represents the runoff efficiency after the threshold rainfall has been exceeded. In figure 1, the threshold rainfall is 4.6 mm. The runoff efficiency is 62 percent.

Table 1 lists the threshold rainfall and corresponding runoff efficiency for 18 various treatments that are or have been under study at the Granite Reef Test Site, 30 miles northeast of Phoenix, Ariz. The results shown in the table are averages for the total time that the treatments were under study.

The importance of considering the threshold precipitation can be

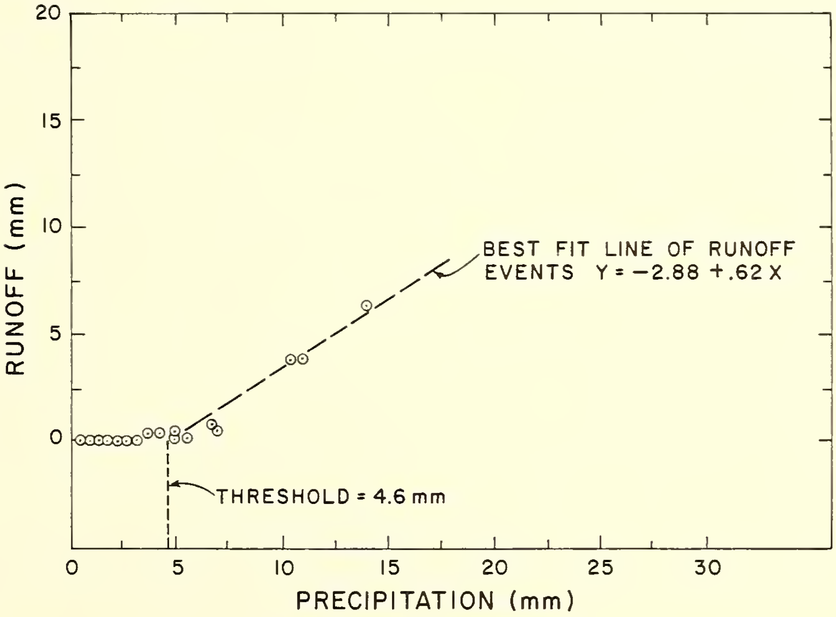

FIGURE 1.--Rainfall vs. runoff for a water harvesting treatment with less than 100-percent efficiency.

shown as follows. For the period 1961 through 1972, total annual precipitation averaged 183 mm from an average of 40 separate rain showers per year at the Granite Reef Test Site. During this period, 50 percent of the showers, representing 11 percent of the precipitation, occurred as showers of less than 2 mm. If the threshold rainfall of a water harvesting treatment had been 2 mm, there would have been no runoff from 20 showers representing 20 mm of potential runoff. For the remaining 20 showers, 40 mm of potential runoff would be lost, for a total of 60 mm, or one-third of the average annual precipitation.

TABLE 1.--Threshold rainfall and runoff for various treatments at the Granite Reef Test Site

Treatment	Length of study	Threshold rainfall	Runoff efficiency
	Years	Millimeters	Percent
Uncleared watersheds	10	3.1	22
Cleared watersheds	10	2.7	32
Smoothed untreated	12	2.3	36
Ridge and furrow	9	2.2	42
Sodium carbonate	5	2.2	47
Silicone water repellent	10	1.8	81
Single-phase asphalt	9	1.7	71
Silicone water repellent plus stabilizer	3	1.2	88
Gravel-covered sheeting	7	1.2	92
Concrete	6	1.1	84
Paraffin wax water repellent	2	.5	95
Two-phase asphalt	11	.5	96
Aluminum foil	10	.4	88
Asphalt fiberglass	7	.4	98
Butyl	12	.3	90
Polyethylene	4	.2	92
Chlorinated polyethylene	6	.1	95
Polyvinyl fluoride	2	.0	100

COST OF HARVESTED WATER

The unit cost of water from a water harvesting system is the cost of collecting plus the cost of storing the water. The cost of collecting the water is a function of unit catchment cost, catchment runoff efficiency, total precipitation, and life of the treatment. Table 2 lists the water costs for nine different types of treatment. The runoff efficiency, life of the treatment, and initial treatment costs are based

TABLE 2.--Water costs for various water harvesting treatments

Treatment	Runoff efficiency	Estimated life of treatment	Initial treatment cost	Annual prorated cost 1/	Water cost in a 500-mm rainfall zone
	Percent	Years	Dollars per square meter	Dollars per square meter	Dollars per 1,000 liters
Land clearing	20-30	5-10	0.01-0.02	<0.01	0.08-0.12
Soil smoothing	25-35	5-10	.04- .06	0.01-0.02	.07- .19
Silicone water repellents	50-80	5-8	.10- .15	.02- .03	.06- .19
Paraffin wax	60-90	5-8	.25- .33	.04- .08	.13- .39
Concrete	60-80	20	1.67-4.20	.14- .37	.50-1.73
Gravel-covered sheeting	70-80	10-20	.42- .58	.03- .08	.12- .34
Asphalt fiberglass	85-95	5-10	.83-1.67	.12- .40	.35-1.32
Artificial rubber	90-100	10-15	1.67-2.50	.18- .34	.49-1.05
Sheet metal	90-100	20	1.67-2.50	.14- .32	.40- .68

1/ Based on the life of the treatment at 6 percent interest.

on the results of 11 years of study at the Granite Reef Test Site and the field installation of 15 operational units constructed in cooperation with private ranchers and governmental agencies. The costs shown in the last column are based on a total annual precipitation of 500 mm per year (20 inches) and do not include the cost of any yearly maintenance, which can be as high as $0.08 per 1,000 liters ($0.30 per 1,000 gallons).

The cost of storing the water is a function of the unit storage cost, the life of the storage, and the number of times the storage will be filled during the year. A typical storage for stock or domestic use might be a grain bin with a plastic liner. Annual cost of such storages has been reported as $1.30 per 1,000 liters ($5 per 1,000 gal) based on a 25-year life and assuming the storage is filled once a year (1). If the storage is filled twice a year, the unit cost of water will be cut in half.

The total cost of water from a water harvesting system can be obtained for less than $3 per 1,000 liters with most of the treatments and probably for as little as $1.50 per 1,000 liters for some of the more economical treatments.

CATCHMENT AND STORAGE SIZE RELATIONS

One of the major problems in designing a useful and economical water harvesting system is the determination of the relative sizes of catchment and storage. A wide variety of catchment and storage-size combinations will provide the required quantity of water when needed. One possible combination might be a large storage reservoir with a relatively small catchment area to collect the water during periods of high precipitation and provide ample carry-over into periods of less precipitation. A second combination could be a relatively large catchment area and small storage.

This combination would rely upon maximum collection during periods of low precipitation. The lowest cost unit will depend upon the relative unit costs of the catchment and the storage. The effect of various costs on the relative sizes of the most economical unit can be shown with the following examples.

Example 1

A stock water system is needed to supply water for 40 head of cattle for 6 months. The precipitation and water requirements by month for a 12-month period are presented in table 3. The catchment material is chlorinated polyethylene, which has an efficiency of 95 percent and a threshold rainfall of 0.1 mm. To compensate for variable rainfall patterns, the design includes the requirement of a minimum of 1 month's water supply in storage during the period of use. The relative sizes of catchment and storage for this data can be determined by several methods (2, 4, 7).

The computer optimization procedure (4) was used to determine 10 combinations of catchment and storage sizes as shown in figure 2. The results show that as the storage size is reduced the size of catchment must be increased. The total cost of the system depends upon the relative unit costs of catchment and storage. Figure 3 shows the total cost of the various combinations if the catchment costs $0.30/m^2 and the storage costs $18.00/1,000 liters. The lowest total cost unit occurred with a relatively large catchment area and small storage volume. Figure 4 shows the total system cost for catchment costs of $1.20/m^2 and storage costs of $8/1,000 liters. With these unit costs, the lowest total cost structure was with a relatively small catchment area and large storage volume.

TABLE 3.--Precipitation and use data for example 1

Period	Precipitation	Use 1/
	Millimeters	Liters
1	22.1	0
2	29.0	0
3	24.4	0
4	19.6	0
5	15.0	0
6	10.9	0
7	48.3	48,600
8	55.1	48,600
9	24.6	48,600
10	27.9	48,600
11	16.8	48,600
12	27.9	48,600
Total	321.6	291,600

1/ Water necessary for 40 cattle for 30 days.

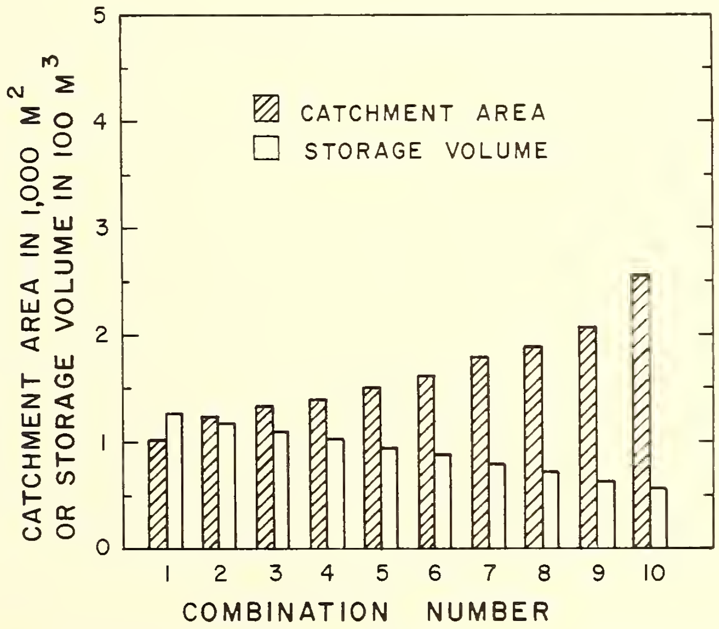

FIGURE 2.--Water harvesting catchment and storage sizes for example 1.

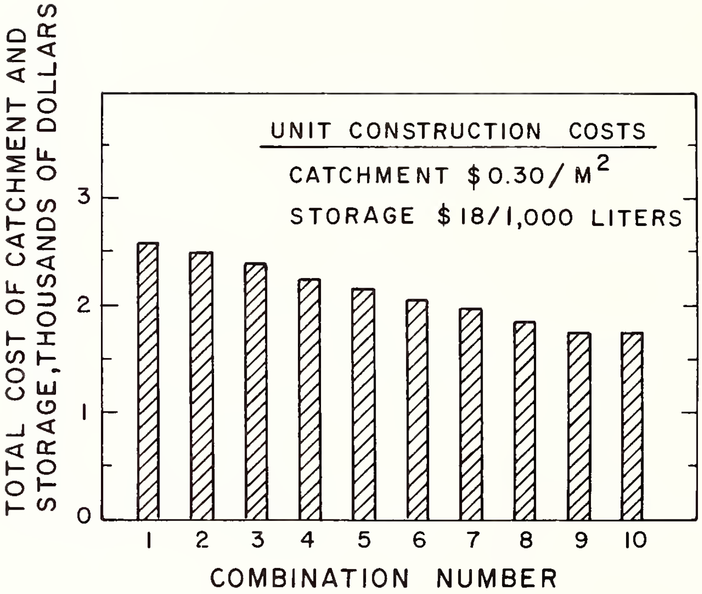

FIGURE 3.--Total cost of the catchment and storage combinations for example 1, with low unit catchment costs and high unit storage costs.

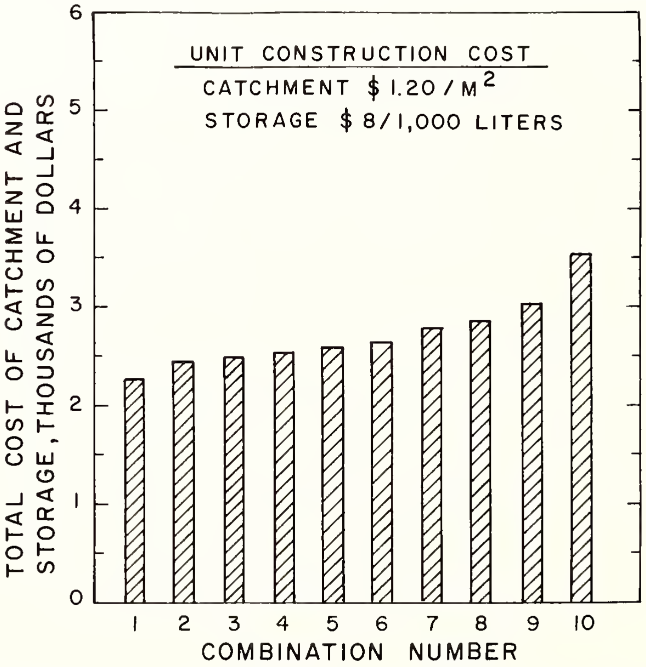

FIGURE 4.--Total cost of catchment and storage combinations for example 1, with high unit catchment costs and low unit storage costs.

Example 2

For this example, we use the same precipitation pattern to supply water to a household of five people for the entire 12-month period. Domestic water requirements range from 38 to 300 liters per capita per day (10 to 80 gal per capita per day (3)). For the example, we will use 163 liters per capita per day for a total of 24,450 liters per month. The total water required for 12 months is approximately the total quantity required for 6 months in the previous example.

Ten combinations of catchment and storage sizes are presented in figure 5. Combination 1 is a catchment area of 1,100 m^2 and a storage volume of 110,000 liters, which are the required sizes if no water overflows from storage. The next seven combinations shown in figure 5 all have the same catchment areas but with succeedingly smaller storage volumes, which will overflow during periods of high precipitation. The total cost for the combinations is shown in figure 6. The lowest cost combination is one with a relatively small storage. This shows that the most economical water harvesting system may not use all the water collected by the catchment. Also, the sizes of catchment and storage are different from those determined in the previous example. This illustrates the difficulty of extrapolating the sizes of catchment and storage to areas other than those for which they were designed. No one combination of catchment and storage sizes will fit all situations. Changing one factor will often result in major changes of the lower cost catchment and storage sizes.

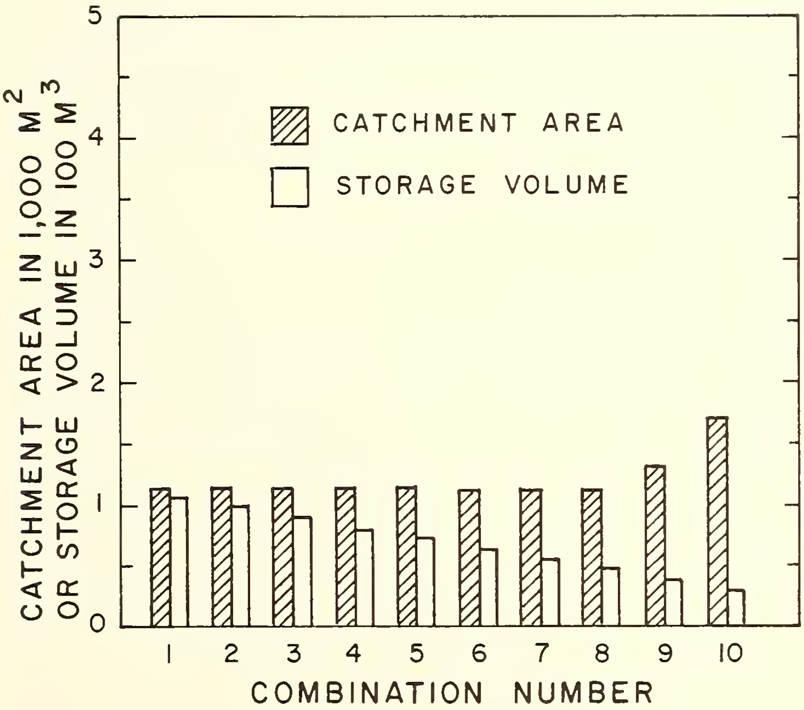

FIGURE 5.--Water harvesting catchment and storage sizes for example 2.

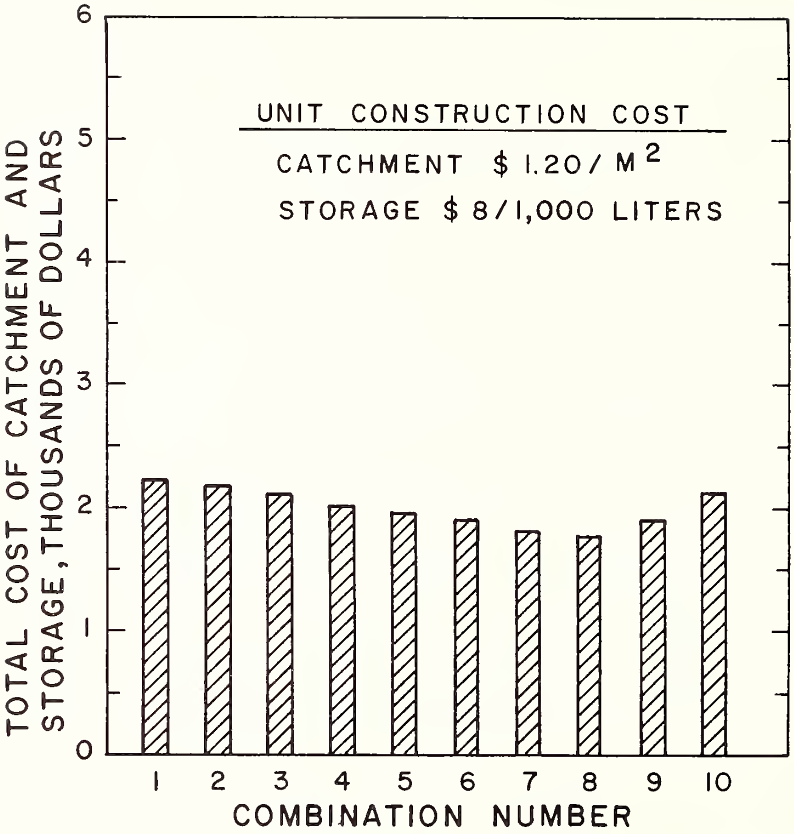

FIGURE 6.--Total cost of the catchment and storage combinations for example 2.

SUMMARY AND CONCLUSIONS

Correctly designed and constructed water harvesting systems are potentially able to supply an adequate quantity of water wherever needed on our rangeland or for our homes. No one system will be the most economical unit for all locations. Factors such as the relative unit cost of catchment and storage, relative distribution of precipitation and water requirement, and total water requirement are important when determining the most economical sizes of catchment and storage.

One factor often overlooked in the selection of catchment materials is the quantity of precipitation necessary before runoff occurs. This quantity of rainfall, termed the "threshold rain," ranged from 0 to over 3 mm as measured from 18 different treatments at the Granite Reef Test Site. This can represent a significant portion of the total potential runoff from areas of relatively low precipitation.

The unit cost of water from a water harvesting system depends on the catchment efficiency, life of the treatment, and the initial catchment cost. Materials and techniques are available that permit the harvesting of water for $0.06 to $1.75 per 1,000 liters in a 500-mm precipitation zone. Annual maintenance and storage costs can add $0.08 and $1.30 per 1,000 liters, respectively.

ACKNOWLEDGMENT

This work was started under the direction of Lloyd E. Myers, former Director of the U.S. Water Conservation Laboratory. He is currently Associate Deputy Administrator, Western Region, Agricultural Research Service, U.S. Department of Agriculture, Berkeley, Calif.

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WATER DEVELOPMENT IN MANAGEMENT OF LIVESTOCK AND WILDLIFE ON MOUNTAIN WILDLANDS

Grant G. Williams 1/

INTRODUCTION

This presentation chiefly concerns livestock management on wildlands, with special emphasis on environmental and water developments and their relationship to harvesting wildland forage. Benefits to wildlife and domestic animals will also be discussed.

GENESIS OF LIVESTOCK HUSBANDRY

Up until the 20th century, most people depended on livestock production for subsistence. Banding individual domestic animals together to form "flocks," or herds, has been a long standing practice, even among primitive societies. This was done primarily for three reasons: (1) livestock protection; (2) livestock identification of ownership; and (3) livestock management.

Biblical examples document the fact that in the Old World, domestic livestock were herded for protection, ownership identity, and management

In Genesis 4:1 and 4:2, we find that Adam and Eve refer to two of their children, Cain, a tiller of the ground, and Abel, a keeper of the sheep. Later in Genesis, we can refer to a story of Joseph who was sold into Egypt by his brothers. When drought came to Joseph's homeland of Canaan, there was plenty to eat in Goshen where the Egyptian Pharaoh ruled. Since Joseph was in favor with the king, he was told to bring his family, flocks, and herds into Goshen. (This event has a modern-day parallel in the drought of the 1930's, when a crash program was put forth to develop nearly every potentially reliable water source in the mountains that would provide a drink for livestock.) In Luke 2:15-18, there is reference to the shepherds who tended their flocks.

Livestock management was probably given little consideration as "flock after flock" roamed as nomadic herds grazing the same areas over and over, concentrating at sources of water. Land abuse is borne out by records from the past, such as those describing the change in the Mediterranean region over the past 8,000 years, documenting devastation from grazing, timber cutting, and other abuses (1). The change in the Mediterranean was caused by a progressive increase in human activity marked by the total disappearance of forest; the encroaching spread of semidesert vegetation as the soil grew more and more barren; and finally desert itself, spreading out from existing desert areas. Further, Plato (1) noted the effects of erosion in his native Greece 2,500 years ago.

THE SECOND GENESIS OF OUR WESTERN LANDS

Early western settlers were strongly dependent on raising livestock

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whose numbers exploded to proportions far in excess of the capability of mountain lands to remain productive. In Utah, there were more than 2 million sheep around the turn of the century (4).

As in the Middle East, the ecology of the arid and semiarid lands was very delicately balanced between soil, vegetation, and climate. Between 1850 and 1900, timber harvesting and livestock grazing of critical watersheds denuded the vegetation to such proportions that disastrous floods hit the communities and valleys below. Most of the wildlands of the West were then public domain, open for use under a philosophy of first there, first served. Local settlers soon found outside operators with large herds moving through steep watersheds, arid foothills, and desert lands. During this period, the wildlands were abused more quickly and completely than any other place in the world.

Around 1900, the public began to demand, through petitions to the Congress, that watersheds and timberlands in the West be withdrawn from public domain and put under Federal control. This marked the birth of the U.S. Forest Reserves, later to be known at the U.S. Forest Service. This also marked the beginning of land management, part of which included water development programs.

When we compare climate, geography, and uses of the resources in parts of the Western United States with those in the Mediterranean region, we find many similarities, as with the Great Salt Lake and salty Dead sea.

RANGE CLASSIFICATION

In the early 1900's, when the National Forest lands were first designated by Congress for protection and management, there were no trained personnel to administer the resource. Job qualifications consisted of being a good horseman, having a knowledge of livestock, and being able to pack a horse. The job was mostly custodial and involved setting up grazing allotments, adjusting livestock numbers to reduce overstocking, shortening grazing season--particularly in spring, establishing fire protection procedures, and issuing timber sale permits.

Throughout the late 1920's and 1930's, curriculums were set up in some Land Grant Colleges and Universities whereby degrees were awarded in range management. This was an important step in attaining sustained yield management of wildlands grazed by livestock.

The job of administering a wildland resource is most complex. Important categories regarding the resource include animal habits and resource complexities.

Animal Habits

Grazing habits of sheep are generally controlled to a large degree by herding. Herding can be used to regulate water frequency and to direct the sheep to forage areas. On the other hand, habit control in cattle is usually done by fencing and salting. In both cases, range deterioration takes place first near water.

Resource Complexities

Vegetation

Eleven different vegetative types are noted in the U.S. Forest Service Range Environmental Analysis Handbook (3). Most individual allotments on a forest have many of these types in various combinations, each with its particular environmental requirements. With so many vegetative types, an adequate range management program is necessary but difficult to establish with livestock. This challenge is complicated by water distribution in or among vegetative types.

Water--Factor of Suitability

For a particular class of livestock, a range is considered to be suitable if it is accessible to livestock, produces forage or has the potential, and has adequate water. It is classified as secondary range if it meets all the requirements for forage production, soil stability, terrain, etc., but lacks water. Secondary range is not included in the indicated grazing capacity of range allotments on the National Forest lands. The facet of range improvement work--changing from secondary to suitable range--is most challenging.

The key to any range use generally involves an evaluation of the basic principles governing range suitability: (1) steepness and length of slope, (2) natural barriers, and (3) amount and distribution of water. Any evaluation guides may require modification to meet specific field conditions, but from my herding and administrative experience, I feel the guides should be more restrictive than liberal. We are only damaging the resource by being too liberal.

Terrain and length of slope can easily be improperly evaluated when doing a range inventory. On long steep slopes, we are faced with either sacrificing the productive areas adjacent to water or not grazing forage-producing areas farther away that would otherwise be very productive. Experience has shown that sacrificing the productive areas adjacent to water must be given preference to not grazing the resource. Development of other water supply sources can eliminate some of the problems associated with total dependences on naturally occurring supplies located on marginal lands.

WATER DEVELOPMENT PROBLEMS

Problems associated with water in the management of livestock are made more complex by extreme precipitation differences from location to location. A graphic portrayal at some mountain and valley precipitation stations along a line from San Francisco to Denver is shown in figure 1. Many desert areas may receive 4 to 5 inches of annual precipitation, while slopes less than 20 miles away receive in excess of 40 inches annually.

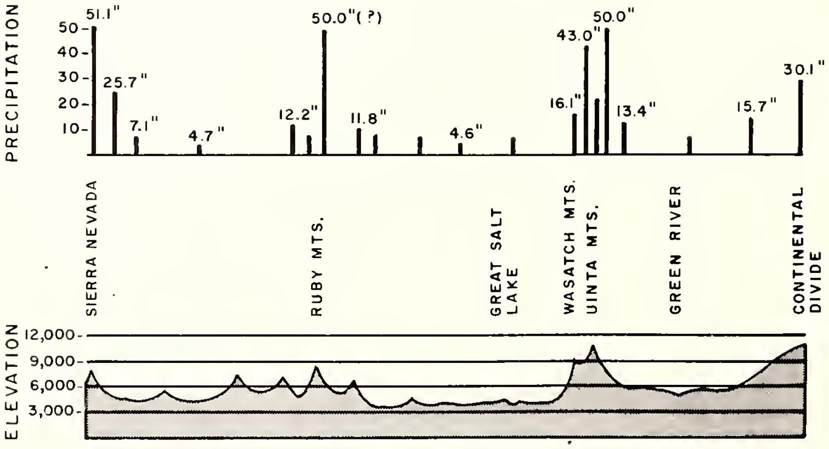

FIGURE 1.--Graphic portrayal at some mountain and valley precipitation stations along a line from San Francisco to Denver.

The form of the precipitation and the season in which it falls influence greatly the water balance as it relates to livestock grazing. A typical mountain range precipitation pattern is illustrated in figure 2 for the Parrish Plots in Utah. At this location, 93 percent of the total precipitation falls as snow. During the grazing period of July, August, and September, approximately 1.7 inches falls as rain. Such a distribution requires that the precipitation from snow provide a ground water source to feed springs and streams for use during the grazing season. In contrast, snowpack-rain patterns for two other locations (fig. 2) are considerably different from the Parrish Plots. These differences create water development situations that are unique to every management program.

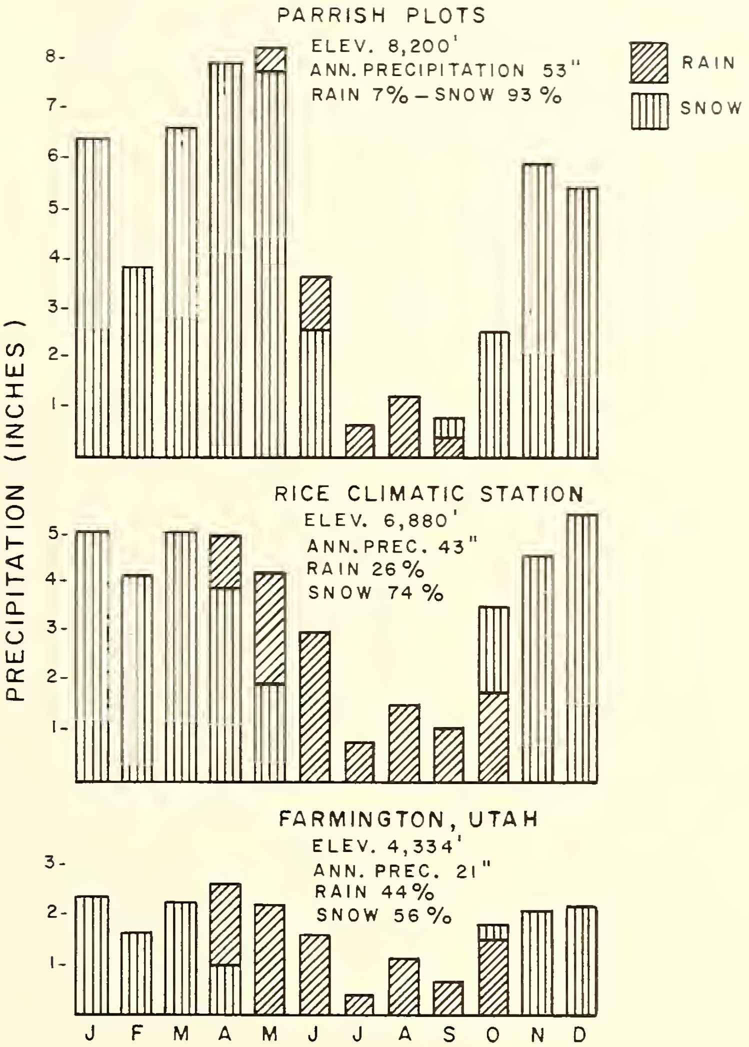

FIGURE 2.--Seasonal snowfall and rainfall patterns at three elevations on a mountain watershed.

When the bulk of the water needed for livestock must come from water developments and small streams that are fed by water sources from winter snowpacks, complex interractions occur involving geology, vegetation, soil, terrain, wildlife, and environmental restraints. If the watering area is in a steep, narrow canyon, the soil on slopes and along stream channels will be disturbed when large herds of sheep come to water. Cattle in steep terrain and narrow-bottomed canyons will concentrate along the stream, fully graze the forage there, and then go up the slopes only as far as necessary to get forage. Cattle usually need their water requirements satisfied every day, especially when the weather is hot and when the forage is more mature. Sheep under more control by herding may not require, and are usually not allowed, water more frequently than every 2 or 3 days depending on climatic conditions.

EVOLUTION OF WATER DEVELOPMENTS IN MANAGEMENT

When the West was first settled in areas where there was limited water, grazing with stock depended on snowbanks or drifts for a source of water. This created serious problems of grazing before vegetative readiness and resulted in compaction of the soil and erosion damage. A comparison situation existed on desert areas when there was very little water initially. In those early years of the West, herds of sheep and cattle competed everywhere for forage and water. It was the responsibility of the camp tenders to scout the hill and valleys for water. If water or snow was found, they would move the herds, even at night, to get there before other herders could move in.

Man's first real effort to provide water was probably by use of an ordinary shovel and manually dammed ponds at small streams, springs, or intermittent streams, where livestock could get a drink that was not half silt or stagnant and filled with feces or wigglers.

When herds of livestock came to water at small mountain streams, typical of many areas of the West, the streams immediately became muddy. The stock would then run up and down the stream to get a clear drink of water and, in reality, made the situation worse. As range conditions became more depleted farther and farther from the streams, it became evident that water in larger volumes must be provided. Before mechanized equipment, ponds or dugouts were constructed, with teams of horses using plows and scrapers. Not many terrains were suitable for this type of water development, but it did satisfy a need until modern equipment became available in the form of tractors.

At about the time ponds were being built with team and scraper at lower elevations, log troughs (fig. 3) were used at the more isolated small springs of higher elevations. This laborious manual effort involved use of crosscut saw, axe, and adz to hollow out logs to hold water. Depending on volume of water and number of livestock to be watered, various units of log troughs would be installed. When more than one unit was desired, the succeeding logs were placed at a lower step to allow the water to run from trough to trough by gravity flow. The log trough, as most any facility, required maintenance. The principal problem was drying and cracking, which created leaks in the trough. These were mended by chinking burlap mixed with tar in the openings.

One more advanced step was the plank trough (fig. 4). This was made by using planks cut from selected logs with a minimum of knots and checks. The planks were bolted together at the spring site, and the joints were tarred to make the trough waterproof. Troughs were generally 10 feet long and were arranged in series as needed. The troughs also required maintenance.

Metal water troughs (fig. 5) are probably the most common watering

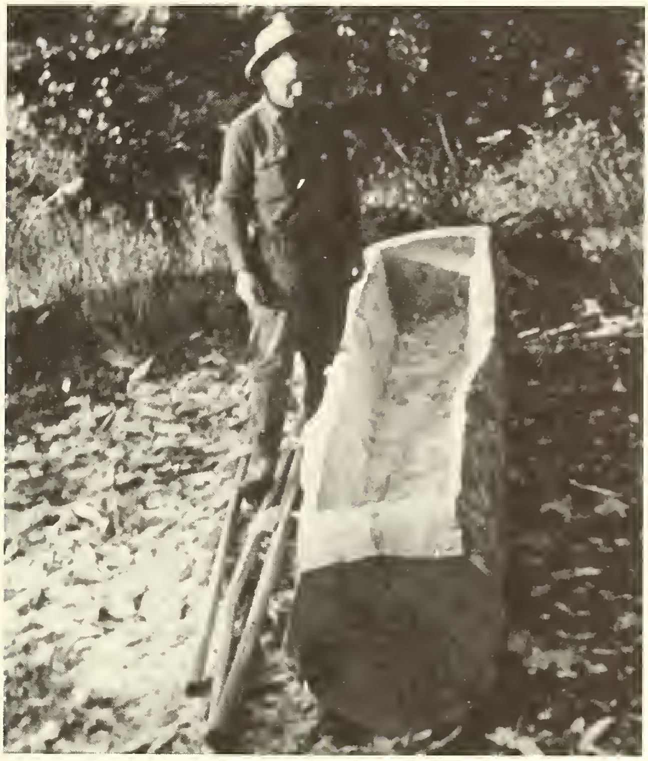

FIGURE 3.--Water trough hewn from a tree.

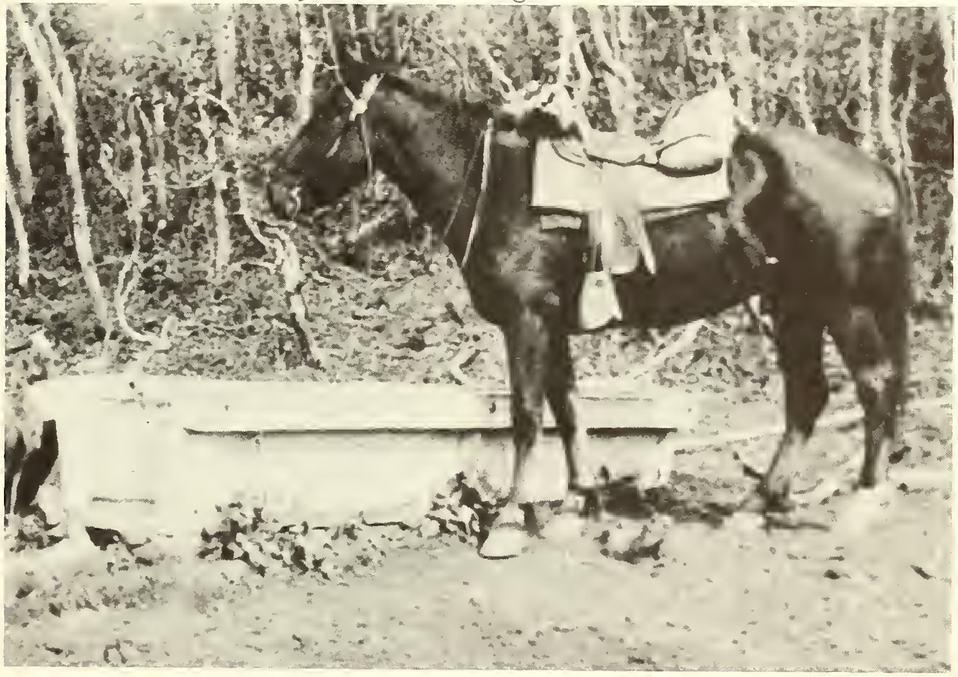

FIGURE 4.--Plank water trough fabricated by bolting.

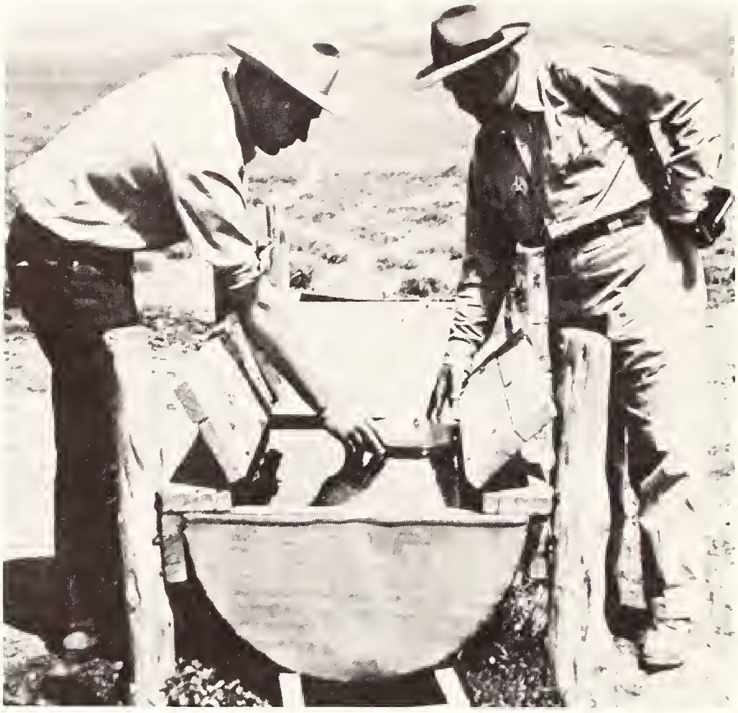

FIGURE 5.--Galvanized metal water trough. Trough can be extended to any length desired by using open end sections.

facility installed during the past 20 to 25 years. They are relatively easy to install and hold up well with a minimum of expense. They are usually made in 10-foot sections, and can be either combined with open-end sections held together with compression bands to extend them to any length desired or assembled in series as described previously. A float-valve arrangement is generally used to permit flow into the unit as the water is used. Baffle planks protect the float valve from being damaged. Maintenance is minimal for metal troughs.

Metal stock tanks provide an excellent watering facility, and with minimum maintenance. As with troughs, the height of the tank must be low enough for calves to be able to drink with relative ease.

Water hauling is a versatile system that can be used where the terrain will permit tank trucks to deliver water to portable troughs. This system can be expensive if roads must be built to areas where water is needed. However, it is versatile in that water can be provided where forage could not otherwise be utilized. The time demands of hauling water create some difficulty in attaining proper livestock operator cooperation. Investment in equipment may also discourage cooperation, especially for small operators.

Troughs, filled by hauling, can be located differently each year to avoid excessive trampling, which invariably destroys the plants in the vicinity of permanent water developments. When an area has been properly grazed, tanks, already located ahead of the herds, are filled with water and cattle move on themselves.

A study was made in 1966 on water hauling costs on the Fishlake National Forest (table 1). The average costs ranged from $1.99 to $0.73 per animal unit month (AUM). These costs did not reflect road construction or road maintenance. Most roads were already in existence. Also, costs have spiraled greatly as part of the current inflationary trend. Since 1966, costs have increased at the rate of approximately 6 percent per year. This would reflect a 42-percent increase over the past 7 years. Thus, the most expensive adjusted water hauling cost would now be approximately $2.85 per AUM, and the least expensive cost would be $1.05 per AUM.

TABLE 1.--Water hauling costs on the Fishlake National Forest in 1966. Costs do not include road construction or road maintenance

Unit	Total AUM	Total costs	Cost per mile water hauled	Cost per AUM	Cost per 1,000 gal 1/
		Dollars	Dollars	Dollars	Dollars
Circus Hollow	188	374.12	0.41	1.99	6.63
Halfway Hill	197	360.00	.66	1.83	6.10
Nixon Field	224	362.00	.47	1.62	5.40
Brown's Hole	757	847.00	.40	1.12	3.73
Lost Creek	1,897	1,384.81	.52	.73	2.43

1/ 1 AUM = 300 gal (10 gal/cow-day, 30 days/month).

Beef cattle prices in Utah, according to the Utah Agricultural Statistical Report (4), have increased about 59 percent from 1966 through 1972. Based on these figures, water hauling is still well within the scope of being financially feasible.

Stock watering reservoirs are larger than the ponds referred to previously and are built with heavy equipment on intermittent streams or small springs where other water developments are less practical and expensive. In most cases, these reservoirs depend on supply from overland flows that occur in the spring or from high intensity summer storms. A disadvantage of the system is that the water tends to become stagnant unless frequent summer storms provide overland flows. In certain areas, the soil may be too porous to hold water. If this condition exists, the reservoirs must be lined with some form of impervious layer.

A "rain trap" (2) is one of the most practical ways of providing water where there is suitable range and forage for livestock (fig. 6).

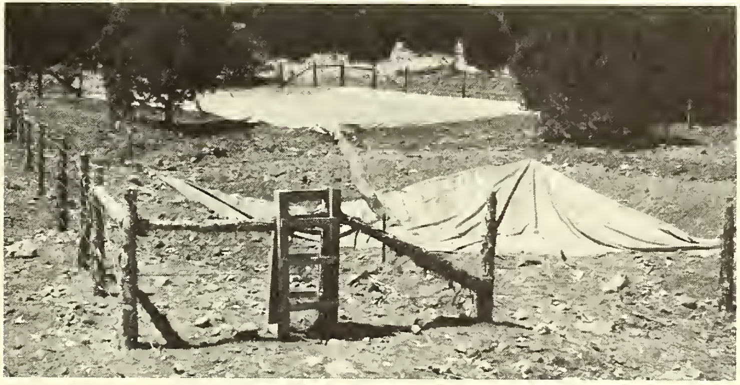

FIGURE 6.--Rain trap installation using a synthetic rubber catchment and one-piece storage bag.

This term was coined in Utah by C. W. Lauritzen (deceased) of the Agricultural Research Service, a group of business leaders associated with butyl rubber manufacturing, and the author on a field trip over the Fishlake National Forest where 10 to 15 installations have been constructed.

Water rights generally have been fully appropriated for all known springs and streams. If we are to provide water, then it must be from another source. A rain trap system, to intercept and store the precipitation before it enters the soil mantle, provides such a source.

RANGE CLASSIFICATION CONVERSION

Let us use an actual example of an allotment situation with suitable range, either reseeded or sprayed to attain production, and yet classified as secondary range because of water shortages. The allotment is the 19,520-acre South Creek Allotment on the Fishlake National Forest. Before water development, 18 percent (3,500 acres) of the allotment was classified as primary range, and 28 percent (5,500 acres) was classified as secondary range. The remaining 54 percent (10,500 acres) was considered unsuitable and nonrange. By using three rain traps on the allotment, 3,900 acres of the secondary range was converted to primary range, which resulted in 8 percent secondary and 38 percent primary--more than doubling the primary range. The water development allowed the cattle to graze approximately 3 miles from water, and hence resulted in the conversions.

PLANNING FOR WATER DEVELOPMENTS IN MANAGEMENT PROGRAMS

If there is one area of concern in range management over the past 30 years of service in a land managing agency, it is the crying need for adequate funding to do a complete development job with revegetation and water for management of livestock on mountain ranges. Revegetation funds, when allotted, can be used only for rehabilitation and building reseeding protection fences. Another allocation is made to build management fences and water developments. The latter allocation is usually woefully inadequate because it must also be used for maintaining existing improvements, fences, and water developments. If the allocations are for watershed improvement, then none can be used for water developments. A rehabilitated watershed that had been depleted is incomplete without proper water development for livestock. If the water is not developed as part of the total program, then backlogs build up, leaving the water program woefully lacking. Unfortunately, allocations are directed to the resource from which most receipts are derived, or when the political pressure can be generated. Many times in the past, these resources have been timber and recreation.

Overgrazing has given the livestock operators a bad name as "spoilers of the resources." However true it may be, we should be putting maximum efforts into restoring the land to its optimum productivity to provide for the future. The future is now in the sense that we need to be producing all that a given unit of land can produce on a sustained yield basis. Forage without water on a mountain range results in poor utilization of the resource, but suitable range to graze with maximum water development and intensive management result in a thrilling success story for which we can be proud.

SUMMARY AND CONCLUSIONS

1. Historically, livestock have been banded into flock or herds for protection, ownership identity, and management. In most instances,

the need of livestock bands for both forage and water has had an impact on land that would not have been as great with livestock dispersion.

2. A natural or developed water supply, sufficient to harvest available forage, is one of the most important requirements for grazing mountain watersheds, assuming no other critical limitations on grazing.

Great strides have been made in developing water: (a) ponds made manually by shovel; (b) log troughs hewn from tree stumps with adz and axe; (c) ponds built by a team of horses using plow and scraper; (d) plank troughs made by cutting, joining, and waterproofing planks; (e) reservoirs built with bulldozers; (f) metal troughs or tanks with float valves; (g) water hauling with trucks to water tanks; and (h) rain traps to intercept and store precipitation.

The latter, in my opinion, will become the answer to providing water where suitable forage producing ranges cannot now be used. Cost is important, but with demand for more red meat the end will justify the means.

3. Intensive management is a must in planning any water development. Otherwise, the development may end up as a negative factor rather than as an assest to range and watershed improvement. We must make the public and Congress aware of the need for more funds to do a better and more complete job of new water development on our important range-watershed lands. It must be pointed out that inexpensive water developments have already had improvements placed at the site.

Filings and adjudications have been made for nearly all of the water in the West. However, to date, no known restrictions have been placed on interception of falling rain and snow to impervious collection aprons that deliver practically 100 percent of the water for consumption use such as livestock watering.

Also, in all developments, we must consider the needs of wildlife and habitat enhancement.

4. The water development techniques discussed are limited to the ones more commonly found in mountainous areas. There is a need to perfect the rain trap for water development, where it is practical to use on our mountain watersheds. I believe many problems with water development systems could have been avoided with dedicated interest and followup by the individuals responsible for the management programs. Also, many apparent problems can be corrected by changes in materials and designs used when developing the rain trap systems. It is my sincere desire that a positive action program will be the product of this symposium.

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DISCUSSION

SESSION I--Herman Bouwer, Chairman

A. HARDAN: Mr. Chairman, first I would like to add a comment on the historical aspects of water harvesting presented by Mr. Myers. In Iraq, we have indications that some forms of water harvesting were already practiced long before 2000 B.C. and maybe as long ago as 4500 B.C. around Ur areas. Furthermore, along the desert roads from the Arabian Gulf to Mecca, there still exist many systems of water harvesting to support the caravans along the roads. In many areas, these systems are distributed at intervals of 10 to 20 miles, Several of these water harvesting mechanisms could be traced back to the early Islamic period (over 1,300 years ago); others predated it. The sites for these systems were carefully selected with respect to topography and the presence of impervious shallow bedrock catchment and storage areas. Secondly, I would like to raise a question and a comment to all speakers regarding the large-scale practical use of water harvesting systems and how dependable the proposed systems are. Keeping in mind the remoteness of the locations, the low level of technology, and the drastic variations in total, intensity, and frequency of rainfalls in areas where water harvesting is needed, we can easily recognize the great risk in depending solely on water harvesting. This is especially so in low rainfall areas. We are all aware of the drastic variations in rainfall that have hit many areas in Africa and Asia during the past several years.

This dramatic and large-scale unpredicted shortage of rainfall has clearly demonstrated that no matter how good and sophisticated our calculations and predictions, we just can not risk the lives of humans or livestock by depending only on water harvesting. The question at this point is: What are the levels of total, intensity, and frequency of rainfalls that may assure us of the presence of enough water to be harvested by the proposed mechanisms? Also, what about considering water harvesting as a supplementary source to the quantity and/or quality of ground water obtained from drilling tube wells in selected areas?

L. MYERS: Mr. Hardan's word of warning is well taken. There are areas where water harvesting is not feasible. Arica, Chile, for example, has experienced periods of zero rainfall that have lasted as long as 5 years. There are other areas where water harvesting must be practiced with caution because reliable precipitation records are not available and unexpected drought is a real hazard. Water harvesting should not be used to establish permanent human populations in such areas unless emergency water supplies are available. These emergency supplies can involve water hauling or, as Mr. Hardan suggests, ground water supplies which are too limited in quantity or quality to serve as a permanent and complete source.

We should not assume that the major application of water harvesting procedures will be in arid regions. There are many areas of relatively high rainfall where adequate ground water and surface water supplies are not available. Many of these situations occur when ground water is highly saline or when usable ground water aquifers do not exist. Although the practice of water harvesting may have originated in arid regions as a matter of necessity, the greatest use of water harvesting principles will probably occur in regions of considerably higher rainfall.

Mr. Hardan is to be complimented for cautioning us concerning an important point that other speakers, including myself, failed to mention. I am sure that he did not intend for this word of caution to cast any doubt on the potential value of water harvesting to arid regions.

J. BOHNING: What is the amount of evaporation from open water surfaces in southwestern Australia?

M. HOLLICK (for W. Burdass): Annual evaporation in southwestern Australia varies from about 900 to 2,000 mm (36 to 80 inches). This creates storage problems, particularly when it is desirable to carry water from one year to the next. At present, there is no evaporation control method which would be recommended except in emergency situations.

H. VELASCO: What were the rates of application of silicone and paraffin wax?

G. FRASIER: The paraffin wax was applied at a rate of 1 1/4 to 1 1/2 lb/yd^2. The silicone water repellent was applied at a rate of 500 lb/acre.

R. SMITH: This is perhaps more of a comment than a question of Gary Frasier's presentation. Without a detailed knowledge of your computer program, it nevertheless seems that the economic analysis you employ is shallow on at least two points. First, the comparison of systems on the basis of cost per init volume under any ratio of unit costs for storage and collection is somewhat specious, is it not, without considering probabilities of length of drought experienced (with use of the proposed system) and cost of supplying water from some other source (hauling, perhaps)? Second, in light of the above, is it not much more significant, in a study of storage sizing, to see how a certain amount of storage performs for certain "patterns of rainfall" as you said your model includes as a variable, and the economics of such eventualities?

G. FRASIER: There are many ways in which the most economical sizing of catchment and storage could be determined. The computer model I used should not be considered as the final answer because of the items you mentioned such as probability of drought. I was trying to show that there are many interrelated factors which should be considered in catchment and storage design. We still do not have all the answers for determining the most optimum unit. The user must decide what he wants to use as a criterion.

K. COOLEY: What problems does wind cause the Coupled Expanded Polystyrene Asphalt Chipcoated (CEPAC) rafts?

C. B. CLUFF: Wind is a problem with unattached expanded polystyrene sheets. Several such sheets have been blown by the wind over a mile from the pond. Since the sheets have been coated with asphalt and gravel chips and coupled together, there has been no wind damage.

The rafts have been placed on a typical unfenced stocktank. The raft is anchored in the center of the tank and cattle can continue to have access on the perimeter.

The raft would have to be removed or reduced in size as the water level drops in an unfenced tank. The stock would badly damage the raft if all the water was covered. It should also be mentioned, however, that there would be much less chance of the stocktank going dry with an evaporation cover.

SESSION II, Part 1--Sol Resnick, Chairman

BITUMEN, OIL, AND CLAY SURFACES ON A DEEP SAND TO INCREASE RUNOFF FROM CATCHMENTS FOR EXCAVATED TANKS IN WESTERN AUSTRALIA

I. A. F. Laing and A. L. Prout [1]

INTRODUCTION

In the south coastal areas of Western Australia, stock water supplies are stored in excavated tanks and rely on runoff from pastured areas or "roaded" catchments to fill them. Potable underground water is rarely found.

Soils

Soils in the area are quite suitable for the construction of excavated tanks but frequently pose a problem of poor catchment yield largely because the soil surface is sandy (5). Topography is flat and slopes generally average less than 3 percent.

The soils are generally formed on a dissected laterite landscape and are predominantly sandy surfaced overlying ironstone gravel and clay. Soils with clay occurring less than 40 cm from the surface are found infrequently in these areas (see map, fig. 1). When the clay is more than 40 cm from the surface, construction of clay-covered roaded catchment is expensive (greater than $A370 per hectare).

Rainfall

The problem of poor catchment yield is further aggravated by low intensity rainfall spread evenly throughout a long growing season of 7 months. Rainfall has been recorded at Kojaneerup (30 km from trial plots) for a period of 46 years. The incidence is typical of a Mediterranean-type climate with a cool, wet winter and a hot, dry summer.

The following is a summary of available rainfall data, [2] in millimeters, at Kojaneerup (46-year average):

J	F	M	A	M	J	J	A	S	O	N	D	Mean annual
17	18	30	34	53	63	53	51	47	46	29	21	460

Mean number of day per year receiving more than--

25 mm/day	1.8
12.5 mm/day	7.0
7.5 mm/day	15.3

Mean number of wet days per year is 111

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[1] Research officer, South Perth, and irrigation and drainage adviser, Albany, respectively, Soils Division, Department of Agriculture, Western Australia.

[2] Commonwealth Bureau of Meteorology records, Perth.

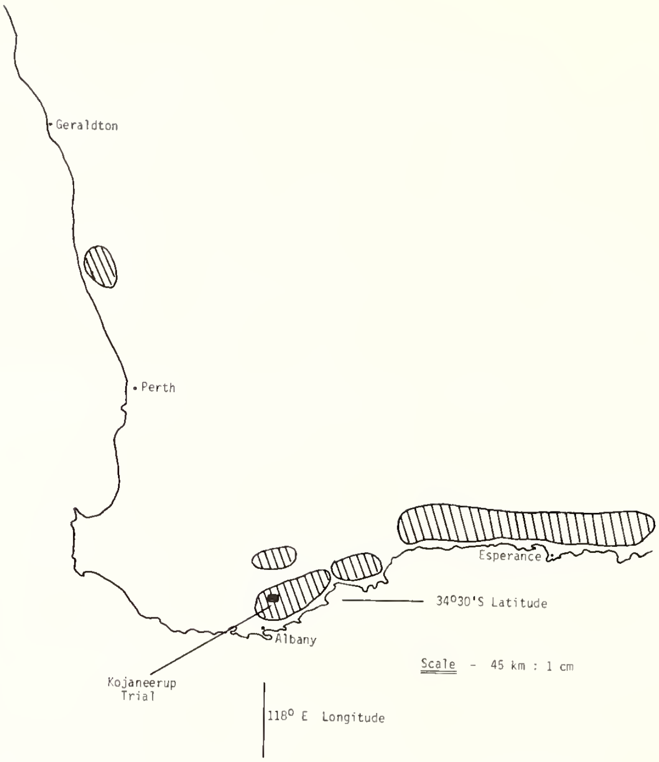

FIGURE 1.--Locality of trial and approximate extent of areas with similar deep sandy soils (hatched).

From 3 years of pluviometer records at the trial site, daily rainfall was less than 1 mm on approximately half the days on which rain was recorded.

Sandy soils and a long growing season with well-distributed rain lead to active pasture growth in most years. This pasture growth (subterranean clover and annual grasses) further reduces the runoff to excavated tanks.

Water Harvesting Background

In an earlier demonstration on this soil type, Prout applied a heavy fuel oil (residue from a ship furnace fuel supply tank) to a small plot, and observed that runoff resulted from very small showers of rain. The results were so encouraging in terms of short-term durability, cost of material, and effectiveness in producing runoff, that a replicated trial was designed to compare runoff production from several different treatments.

Myers et. al. (4) and Kelsall 3/ have both emphasized the extreme importance of foundation soil preparation in bitumen catchment preparation.

Wilke and Wendt (6) applied heavy fuel oil to in-situ soil, and measured a high percentage runoff.

3/ Kelsall, K. J. Construction of bituminous surfaces for water supply catchment areas in Western Australia. Public Works Dept., Perth, Western Australia. 13 pp. 1968. (Duplicated notes.)

Purpose

The prime aim of the work reported here was to create catchment surfaces having low infiltration rates but not necessarily having great mechanical strength to allow vehicle movements. If respraying was necessary, vehicle pathways could be planned, and the intervening catchment surface could be reached by a hand lance on a hose.

Trial Site Description

The soil was typical of the district with the following profile:

Centimeters	
0 - 40	gray sand
40 - 50	pale-yellow sand
50 - 60	coarse pisolitic ironstone gravel
60 +	yellow-brown mottled clay

Particle size distribution of the 0-to 40-cm horizon was as follows:

	Percent
Coarse sand (2 - 0.2 mm)	26
Fine sand (0.2 - 0.02 mm)	76
Silt (0.02 - 0.002 mm)	0
Clay ($\angle$ 0.002 mm)	2

The trial site has previously been sown to an annual pasture of subterranean clover and grasses, and had a natural slope of 1.5 percent.

MATERIALS AND METHODS

Trial Design and Plot Preparation

The trial was of randomized block design, with eight treatments and three replications. Each of the 24 plots measured 7.5 m wide by 30 m long, and each was formed by a road grader into a wide Vee cross section with a central drainage line running the length of the plot. All plots ran straight downhill and had slopes similar to the natural ground slope (1.5 percent). The side slope of all plots (from crest to trough) was approximately 10 percent. Runoff from each plot was discharged centrally at one end, where the runoff measuring equipment was installed.

All plots were left smooth after forming with a road grader, and herbicide and surface sealing materials were applied to the smooth surfaces.

The trial site was fenced to exclude stock.

Treatments

Treatment 1

A commercial waterproofing oil was applied at 1.1 liters per square meter (Shell WPO--the least viscous of a range of three waterproofing oils available). This material consisted of a heavy fuel oil diluted with power kerosene to a low viscosity, plus a small amount of a wax formulation. 4/

4/ Badge, G. Personal communication; Shell Oil Co., Perth, Western Australia.

Treatment 2

Waterproofing oil (as in treatment 1) was applied at 0.6 l/m^2 as a priming layer; followed by a rapid setting bitumen emulsion as a sealing layer, applied at 0.6 l/m^2. A 2-week curing time was allowed for the waterproofing oil (to ensure loss of volatile oils) before applying the emulsion.

Treatment 3

A slow-setting bitumen emulsion was sprayed onto moist, finely cultivated soil as a primer at 1.3 l/m^2. This was then sealed with a slow-setting bitumen emulsion at 0.6 l/m^2.

The priming layer of bitumen formed a plastic mixture with the cultivated sand surface within about 24 hours of application, and this bitumen and sand mixture was compacted with a vibrating plate.

Treatment 4

A diluted, slow-setting bitumen emulsion (one of emulsion to three of water) was applied as a priming layer at 0.8 l/m^2. A sealing layer of slow-setting bitumen emulsion was then applied 2 days later at 0.6 l/m^2.

Treatment 5

A heavy fuel oil (high viscosity furnace fuel) diluted with power kerosene (three to one) was sprayed onto a smooth soil surface at 0.95 l/m^2. Dilution of the heavy fuel oil with power kerosene was only necessary to reduce viscosity for spray application at ambient temperature. The minimum dilution of heavy fuel oil was used to enable the greatest reduction of infiltration rate (3).

Treatment 6

Smooth compacted clay. The clay was transported from a nearby borrow pit, and placed as a compacted blanket 8 cm thick on the plots, using a two-wheeled scoop behind a wheeled tractor. During placement of the clay blanket, many tractor movements were required, and considerable compaction resulted. The clay was generally drier than optimum for compaction.

Some leveling of the clay surface was necessary to give the final finish. This light grading was done with a blade on a wheeled tractor.

Treatment 7

Mini-roaded clay.--A clay blanket was prepared as for treatment 6. Regular furrows were then superimposed on the sloping clay surface, at approximately 40-cm intervals along the length of the plot. (See fig. 2.) Marsh 5/ has proposed miniroading as a technique that gives greater intensity to the drainage pattern, and this should result in a greater percentage runoff due to more rapid channelization of overland flow. The miniroads were constructed on the lightly cultivated clay plots by a specially adapted roller, of square cross section, pulled by a wheeled tractor.

Treatment 8

Control--untreated sand.--After recording only very small amounts of runoff from this surface, it was discarded as a treatment. Bare, un-

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5/ B. a'B. Marsh, personal communication.

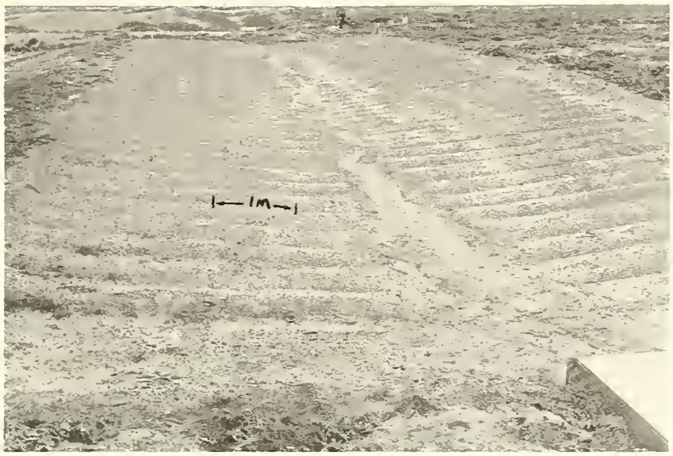

FIGURE 2.--A miniroaded clay plot. Note divisor box in right foreground.

treated sand was an impractical catchment surface and was subject to severe wind erosion.

The previously untreated control plots were subsequently sprayed with another grade of commercially available waterproofing oil (Shell WPO No. 2) at 0.9 l/m^2.

Approximate costs of treatments are presented in Table 1.

TABLE 1.--Approximate treatment costs as of July 1971

Treatment No.	Treatments		Costs 1/
	Primer	Sealer	
			$A/ha
1	WPO 2/		1,300
2	WPO	RSE 3/	1,500
3	SSE mixed with sand, rolled	SSE 4/	1,800
4	Diluted SSE	SSE	1,100
5	Diluted HFO 5/		400
6	Smooth clay		500
7	Miniroaded clay		500
8	Control--untreated sand (up to 9/14/72)		50
8	WPO No. 2 (used after 9/14/72)		1,300

1/ Costs for oils and bitumens refer to materials only; that is, grading plus herbicide plus oil and/or bitumen. The clay costs include application costs but no herbicide. Extra costs for oils and bitumens would include transport costs and field application costs.

2/ Waterproofing oil.

3/ Rapid-setting bitumen emulsion.

4/ Slow-setting bitumen emulsion.

5/ Heavy fuel oil.

The oils and bitumen emulsions were all applied with a hand-operated spraying unit. Spraying was generally done to the point of runoff, except where the oil was to be followed by a seal coat of bitumen emulsion. In such cases (treatment 2), the waterproofing oil was applied at approximately half of the rate merely in the interest of keeping the treatment cost down to a practical level. Infiltration of the oils was very rapid, and much heavier rates could have been applied than were actually used. The bitumen emulsions were applied to the point of runoff, and to put more of the emulsion on would have required another application.

The slow-setting emulsions were not applied if rain was expected within the following 36 hours.

All bitumen and oil plots were treated with herbicide prior to the sealing treatment applications.

The herbicides used were: A mixture of 40 percent W/W atrazine plus 40 percent W/W amitrole at 12 kg/ha, and 80 percent W/W bromocil at 7 kg/ha.

Half of each plot was treated with each chemical. Twenty-five millimeters of rain fell on the plots after the herbicide application and before any sealing treatments were applied. Eight centimeters of compacted subsoil clay was sufficient to prohibit growth of any annual pasture species, and herbicide application to the clay treatments was not necessary.

Runoff Measurement

Runoff from each plot was split into 11 equal parts through a divisor box (2), and the runoff from the central slot (one-eleventh of total) gravitated into a reservoir installed below ground level. Each of the slots in each divisor box measured 2.5 cm wide by 10 cm high, with a 2.5-cm space between slots.

Runoff volumes were calculated by water level difference in each reservoir between observations.

The vertical sided reservoirs were open at the top, and a correction was applied to each based on estimated evaporation and measured rainfall between the dates of observation. The divisor boxes were set horizontally or with a very slight fall in the direction of the plot slope. Considerable trouble was experienced with debris being deposited on the floor of each box and across the slots. This problem could be overcome with a settling tank and filter for each box, but this was not feasible. Regular removal of the silt and trash was a practical solution to this problem.

As the trial site was remote from our nearest laboratory (64 km to the nearest District Office), the slots were made wider than optimum to let debris through to reduce blockage. Narrow slots give greater accuracy of measurement, but they are more liable to blocking with debris.

Rainfall Measurement

Pluviograph and standard rain gage records were collected at the trial site for the 2 1/2 years of the trial. The pluviograph was a Rimco 0.25-cm, siphon-controlled tipping bucket transducer attached to an Ott long term recorder. The standard rain gage was a 20-mm diameter, storage-type gage.

Separate Weed Control Trial

Subsequent to initiating the main surface sealing trial, a separate weed control trial was commenced in the early winter of 1972, after germination of the annual pasture. This trial was a randomized block design, with 11 treatments, each replicated twice to give a total of 22 plots. Each plot was 0.004 ha. The treatments were:

A mixture of 40 percent W/W atrazine plus 40 percent W/W amitrole at 6 and 12 kg/ha.

80 percent W/W atrazine at 6 and 12 kg/ha.

80 percent W/W diuron at 6 and 12 kg/ha.

A mixture of 39.5 percent W/W tandex, 13 percent W/W amitrole, and 40 percent W/W 2,2-DPA, at 6 and 12 kg/ha.

80 percent W/W bromocil at 3.5 and 7 kg/ha.

A control - nil treatment.

The herbicides were all applied in the form of wettable powders.

The following cross treatments were superimposed on all plots: Slow-setting bitumen emulsion, water proofing oil, and control (nil treatment).

The cross treatments were applied 12 weeks after the herbicide application, in which time 150 mm of rain was recorded.

The pasture at the site consisted of a mixture of the following annual species:

Trifolium subterraneum cv. Mt. Barker

T. subterraneum cv. Woogenellup

Erodium botrys

Cryptostemma calendula

Hypochoeris spp.

Bromus spp.

Lolium rigidum

Vulpia spp.

RESULTS AND DISCUSSION

Tabulated mean runoff measurements are presented in table 2 in absolute units (millimeters) and as a percentage of rainfall.

In table 3, the treatments and runoff data have been regrouped into three broad categories: Oil primed treatments (treatments 1, 2, and 5); bitumen emulsion primed (treatments 3 and 4); and clay treatments (treatments 6 and 7).

Treatment 8, after September 14, 1972, was grouped in with the oil primed treatments.

Due to the remote location of the trial, visits were at times infrequent and records were lost as a result. During the measurement periods for which records are quoted (tables 2 and 3), runoff and rainfall data were collected at fortnightly intervals.

Summer and Autumn 1972

In this first period of measurement, records were kept from November 11, 1971, to May 18, 1972. The clay treatments and the untreated sand gave very low amounts of runoff, and were significantly less than treatments 1, 2, 3, and 5. A logarithmic transformation of the data showed treatments 1, 2, 3, and 5 yielded significantly more runoff than treatment 4, which in turn yielded significantly more runoff than treatments 6, 7, and 8.

The grouped data in table 3 show the oil primed plots (treatment 1, 2, and 5) to be significantly better than the bitumen primed plots

TABLE 2.--Mean runoff volumes per plot

Treatment	Period of measurement							
	Summer - Autumn 1972		Winter 1972		Spring 1972		Winter 1973	
	Mm	Percent	Mm	Percent	Mm	Percent	Mm	Percent
1	14.9	20.1	20.85	26.6	6.45	15.4	3.55	8.4
2	25.13	33.8	27.2	34.6	11.7	28.0	11.5	27.4
3	16.85	22.7	25.3	32.2	10.85	26.0	6.33	15.1
4	7.15	9.6	20.58	26.2	4.2	10.0	3.2	7.6
5	22.83	30.7	23.9	30.4	5.95	14.2	6.7	15.9
6	2.95	4.0	19.25	24.5	7.25	17.3	12.25	29.2
7	1.88	2.5	17.43	22.2	5.4	12.9	10.1	24.0
8	2.35	3.2	1.13	1.4	13.3	31.8	10.6	25.2
Least significant difference at the 5% level.	11.6		12.3		(1/)		(1/)	
Rainfall	74.25		78.5		41.75		42	

1/ Not significant.

TABLE 3.--Grouped mean runoff volumes

Grouped treatments	Summer-autumn 1972 1,2/	Winter 1972 3/	Spring 1972 3/	Winter 1973 3/
	Mm	Mm	Mm	Mm
Oil primed 4/	20.94	23.98	9.35	8.09
Bitumen 5/	12	22.95	7.53	4.76
Clay 6/	2.42	18.33	6.3	11.18
Rainfall	74.25	78.5	41.75	42

1/ Difference between oil primed and bitumen treatment means significant at the 5-percent level.

2/ Difference between the combined oil primed and bitumen treatment means compared with the clay treatment means was significant at the 0.1-percent level.

3/ Differences between treatment means were not significant.

4/ Treatments 1, 2, and 5 up to 9/14/72. Treatments 1, 2, 5, and 8 from 9/14/72 onwards.

5/ Treatments 3 and 4.

6/ Treatments 6 and 7.

(treatments 3 and 4); and the oil and bitumen treatments considered together were significantly better than the clay treatments.

The poor yield from the clay can mainly be attributed to the dryness of the clay surface during this time period. It was summer and autumn, and day temperatures were warm to hot. A total of 74.25 mm of rain was recorded at the trial site in this time, but the estimated evaporation from a free water surface for the same period was 700 mm (1).

Another reason for poor initial performance of the clay could be in the degree of compaction or surface condition.

The better performance of oil primed plots in comparison with the bitumen primed plots, was probably due to:

(1) The greater depth of penetration of oils compared with bitumens, and therefore a greater depth of waterproofed soil.

(2) Less damage to the oil treated surface by weed growth and by animals.

It was originally thought that treatment of these soils with a heavy fuel oil would be a cheap method of inducing runoff. The cost of the heavy fuel oil was approximately 2.5 cents per liter, and at 0.9 l/m^2 would cost $A255/ha. In actual fact, this was the cost of the fuel oil only, and as application in the field required either heating or dilution, and then spraying, the real cost of the applied treatment was considerably more. One farmer in the district is known to have had a small area treated for a contract price of more than $A1,250/ha.

Winter 1972

In this second period of measurement, records were kept from July 27 to September 14, 1972. All the oil, bitumen, and clay treatments yielded significantly more runoff than the untreated control. The clay treatments were not significantly different from any of the oil and bitumen treatments. This result is in contrast to the previous measurement period. There may have been some extra natural compaction of the clay blanket in this first winter period, leading to extra runoff. Crust formation on the clay surfaces may also have been a factor.

Spring 1972

In this third measurement period, records were kept from September 14 to October 10, 1972. Treatment 8, previously an untreated control, was sprayed with a waterproofing oil on September 14, and, as a consequence, runoff volumes were increased.

No significant differences between treatments were detected in this measurement period, or in the subsequent period in winter 1973, from June 12 to July 11, 1973.

General

The clay treatment plots were graded and rolled originally to give a firm, smooth surface. After more than 2 years of exposure, the clay treatments have all suffered sheet erosion, and the surface of all plots is now scattered with medium ironstone gravel. This mulch of gravel must increase surface detention and reduce the efficiency of clay catchments.

No significant difference was detected between the smooth clay and the miniroaded clay treatments, although actual measured differences between the two treatments were always in favor of the smooth clay. If this is in fact a real difference, it may be due to the method of formation of the miniroads, which left the plot surface rather loose and unconsolidated between the minifurrows. Alternative methods of miniroad formation are being investigated. 6/

There are apparent trends in the percent yields of different treatments (table 2). All the oil and bitumen treatments have shown a decreasing runoff percentage in the three winter and spring measurement periods. Runoff percentages from the clay treatments are erratic. As the oil and bitumen treatments are all relatively thin, on a very permeable soil, and probably subject to leaching losses (at least in the wet months), it is reasonable to assume a gradual loss of efficiency as regards runoff inducement. Reduced efficiency of these treatments may also be hastened by stock damage, oxidation, weed growth, wind effects, and general foot trafficking.

It was hoped to be able to relate runoff yields to rainfall intensity in this trial, but without more detailed runoff data, this has proved to be virtually impossible.

Resistance to Mechanical Damage

Straying stock (cattle and sheep) were a problem at times, and tracks of kangaroos were also seen occasionally. The clay surfaces were least affected by stock. The oil surfaces were still quite soft and plastic after more than 2 years exposure, and although animals left identations in the oil treated surfaces, they seldom broke through into the underlying untreated sand. Treatment 3 surfaces (bitumen and sand mixed, compacted and sealed with more bitumen emulsion) were very robust, and seldom broken by straying animals. Identations from hooves were small in size. Treatment 4 surfaces were the worst affected by animals, and animals had frequently broken through the thin sealing layer, or caused large indentations.

Frequent strong winds are another hazard in the area, and could limit the life of thin sealing layers on poor soil foundations. There was a tendency for the bitumen surfaces (treatments 3 and 4) to be peeled off by the wind. Similar damage was not seen on the oil or clay treatments.

The depth of treated soil for each treatment is listed in table 4. The depth of treatment affects resistance to mechanical damage.

TABLE 4.--Depth of treated layer

Treatment	Thickness or depth of penetration of treated layer
	Centimeters
1	2
2	1
3	11
4	.2
5	2
6	8
7	8
8	2

6/ B. a'B Marsh, personal communication.

Runoff Water Quality From Fuel Oil Treatments

The runoff from a fuel oil treated catchment (on a nearby farm) was sampled. An oily film could be seen on the water surface at the time of sampling, and analysis 7/ showed the content of ether soluble materials to be 1.5 parts per million.

It was not possible to associate these ether solubles with the oil-treated catchment, although this would appear to be the most likely source. Sheep were drinking this water with no apparent ill effects.

Results of Separate Weed Control Trial

Twelve months after herbicide application, and after germination of pasture seeds in the 1973 winter, a visual rating of the plots showed some interesting differences in degree of weed control. See tables 5 and 6.

TABLE 5.--Mean weed control scores 1/ in weed control trial, June 16, 1973

Herbicide treatments			Cross treatments surface sealing materials			
No.	Chemical	Rate	WPO 2/	Nil	SSE 3/	Total
		Kg/ha				
1	40 percent atrazine + amitrol	6	1	0	1	2
2	Do-----------------	12	1	1	1.5	3.5
3	80 percent atrazine	6	1.5	1	1	3.5
4	Do-----------------	12	1.5	.5	1	3
5	Diuron	6	2.5	2	3	7.5
6	Do-----------------	12	3.5	3.5	3.5	11.5
7	Tandex + amitrole + 2,2-DPA	6	2	2	2.5	6.5
8		12	4	3.5	4.5	12
9	Bromicil	3.5	4	44	5	13
10	Do-----------------	7	4	4.5	5	13.5
11	Nil(control)		.5	0	0	.5
	Total		25.5	22.0	29.0	76.5

1/ Rating scores: No weed control, 0; complete weed control, 5. Each score is a mean of two plot ratings.

2/ Waterproofing oil.

3/ Slow-setting bitumen emulsion.

Eighty percent bromocil at both 3.5 and 7 kg/ha, under the cross treatment of the slow-setting bitumen emulsion, gave excellent weed control. Under the waterproofing oil, and the nil cross treatments, this herbicide was slightly less effective, but still gave good control.

Both 80-percent diuron, and the mixture of tandex, amitrole, and 2,2-DPA, at the high rate (12 kg/ha), gave very good weed control under the cross treatment of slow-setting bitumen emulsion. Under the water-

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7/ Government Chemical Laboratories, Plain Street, Perth.

TABLE 6.--Mean weed control scores 1/ (data selected from table 5)

Herbicide treatments			Cross treatments surface sealing materials			
No.	Chemical	Rate	WPO 2/	Nil	SSE 3/	Total
		Kg/ha				
6	Diuron	12	3.5	3.5	4.5	11.5
8	Tandex + amitrole + 2,2-DPA	12	4	3.5	4.5	12
9	Bromocil	3.5	4	4	5	13
10	Do----------------	7	4	4.5	5	13.5
	Total		15.5	15.5	19	50.0

1/ Rating scores: No weed control, 0; complete weed control, 5.

2/ Waterproofing oil.

3/ Slow-setting bitumen emulsion.

proofing oil, and the nil cross treatment, these herbicides were slightly less effective and gave only fair weed control.

A further rating of these plots, in late spring 1973, showed the high rate of 80-percent bromocil (7 kg/ha) to still be the best treatment, with only very few grass plants present.

Weed Control in Main Surface Sealing Trial Plots

The herbicide applications to the main trial plots were not successful in stopping growth of the annual pasture plants. After the first 6 months, repeated spraying with contact herbicides was required to keep weeds under control.

The reason for 80-percent bromocil being relatively ineffective in the main surface sealing trial was probably due to insufficient rainfall between the herbicide application and the sealing treatment application, and some shallow ($\angle$ 2 cm) smoothing done by hand raking in the same time period.

CONCLUSIONS

Considering the initial costs, the likely maintenance costs, and the runoff percentages from oil, bitumen, and clay surfaces, clay catchments appear to be the most practical and economic in this district.

A prerequisite to sealed catchment formation is weed control. Uncontrolled weed growth in bitumen and oiled surfaces is extremely destructive and treatment of the foundation soil with a soil sterilant, or a high rate of a preemergency herbicide, is necessary.

ACKNOWLEDGMENTS

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SOIL TREATMENT WITH SILICONES FOR WATER HARVESTING

Edwin P. Plueddemann [1]

SUMMARY

Sandy soil was treated effectively with an aqueous spray containing a polymer latex and a water repellent. The polymer latex served to bind the soil while the water repellent caused run off of the water. Among commercial polymers tested, an acrylic, and a styrene-butadiene resin (SBR) latex looked most promising. Both a sodium methylsiliconate and a silicone emulsion were effective as water repellents, but the emulsion gave somewhat better results and was much more convenient to use. A mixture of SBR latex and silicone emulsion is stable at 50-percent solids, and may be diluted with water to about 3-percent solids for application to soil.

INTRODUCTION

Treatment of soil for improved water harvesting may become important in regions that receive moderate rainfall, but the soil is so porous that the moisture soaks in and does not accumulate as surface water and does not form a water table at accessible levels for recovery from wells. Rainfall of only 10 in/yr could supply 56 gal/yd^2 if all rain were harvested.

Harvested water could be collected and stored in reservoirs for livestock, wildlife, and domestic use, or run off directly for irrigation and crop production. Soil treatment water harvesting should be a simple spray (preferably from water) of soil with a low cost material to give good soil binding and water runoff during several years of exposure.

Myers (2) has reviewed extensive studies by the U.S. Department of Agriculture on treatment of Arizona soil for water harvesting. Various latex polymers looked promising for soil consolidation, but imparted little water repellency. Aliphatic quaternary ammonium salts rendered soil water repellent, but generally did not penetrate, and erosion soon removed the treatment. An aqueous solution of sodium methylsiliconate penetrated the soil well and provided water repellency during several years of outdoor exposure, but the treatment lacked soil binding properties and suffered from erosion.

Studies in Israel over a 3-year period were reported by Hillel (1) for two types of soil. Solutions of heavy fuel oil performed best in the sandy loam of the Negev area, but did not perform nearly so well in the clay of the Judean hills. The clay of Judea gave best water run off when it was treated with concentrated solutions of sodium chloride or sodium phosphate (Calgon) to form a sodic crust. The treatment was not effective for more than 1 year and allowed a high degree of soil erosion. Treatment with the sodium methysiliconate solution was fairly effective and suprisingly durable over a 3-year period, but it allowed almost as much erosion as the salt treatment.

Three effects were observed in soil treatment: A hydrophobic effect, a structure stabilizing effect, and a surface sealing effect. A treatment should possibly provide all three effects for maximum efficiency, and be sufficiently weather resistant to last over several years.

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Silicones as hydrophobing agents have outstanding weather resistance due to the polymer backbone of alternating silicon and oxygen atoms. Methyl substituents on silicon provide low critical surface tension (nonwetting by water) with complete freedom from imparted color, taste, or odor. Since low coneentrations of silicones have no soil binding properties, they should be mixed with low-cost organic polymeric materials as soil binders.

Emulsion of silicone oils were described by Rooks (4) as convenient forms of textile finishes. Such neutral silicone emulsions will also be most convenient for mixing with organic polymer latexes for application from water. They present much less of a safety hazard than the highly alkaline solutions of sodium methylsiliconate.

Any treatment of soil with organic materials for hydrophobing, binding, or sealing requires that the treatment retain adhesion to soil particles in the presence of water. Studies of the interface in mineral reinforced composites indicate that such adhesion is possible only if chemical and mechanical properties of the interface are controlled within well-defined limits (3).

The polymer must present polar functional groups to the mineral surface in order to compete with water at the interface. Silanol functionality, provided by silane "coupling agents," provides the best water resistant bonds or organic polymers to almost all mineral surfaces. Proper modification with silanols will contribute direct adhesion of tacky or rigid polymers to minerals. Oils or rubbers cannot form water resistant bonds to minerals even with optimum chemical modification (fig. 1). The graph shown in figure 1 is a qualitative representation of the type of bonding between an organic polymer and a mineral surface as measured by peel strength of coatings, shear strength of adhesives, or flexural strength of reinforced composites. The same concept should apply to the water resistance of the bond of any oil, asphalt, wax, or polymer used as a soil binder in water harvesting. Bonding may be obtained through primers or additives that convert the polymer at the interface into a tacky or rigid structure with polar chemical functionality.

A total treatment for soil may require a combination of materials; for example, a sodic crust for structure stabilization and weed control, an organic polymer for surface binding to prevent erosion, a silicone

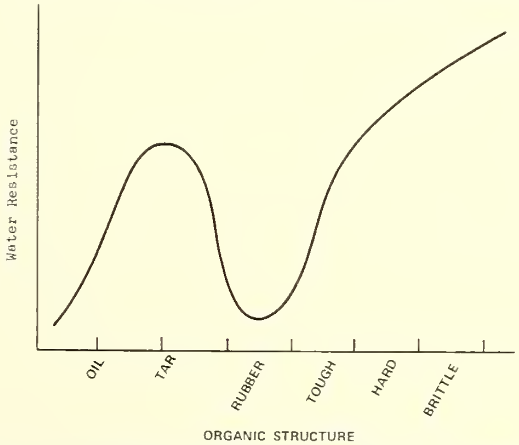


FIGURE 1.--Bonding in silane modified organic-inorganic composites.

for hydrophobing, and a silane coupling agent for promoting water resistant bonding to the soil (antistrip additive). It should be possible to combine the three latter materials in a single aqueous emulsion spray.

Tests

Two samples of soil were supplied by D. H. Fink of the U.S. Water Conservation Laboratory in Phoenix, Ariz. Granite Reef soil is a loose sandy soil typical of much of Western United States, whereas Adelanto is a higher clay soil of the Phoenix Valley area. Soil analyses supplied with the samples were as follows:

Soil	Granite Reef	Adelanto
pH	8.1	7.7
Cations (mg/100 g):		
Ca^{+2}	22.74	22.68
Mg^{+2}	5.56	5.17
Na^{+}	0.02	2.80
K^{+}	0.70	2.48
Sand (percent)	58	35
Coarse silt (percent)	21	22
Fine silt (percent)	16	23
Clay (percent)	7	20

A few preliminary tests (A-E below) indicated that soil binding and water repellency from aqueous treatments were more difficult to obtain with the Granite Reef soil, and since this was the soil of greatest interest, most of our tests were run with this material.

Fifty grams of soil were weighed into a 2-in aluminum weighing dish and tamped down lightly to obtain a reasonably smooth surface. The aqueous treatment was poured over the soil sample and observed as follows:

A. Soak In Time.

After pouring the aqueous dispersion over the sample, the time was measured until the surface lost its shiny, wet appearance. This time varied from a few seconds to over 20 minutes. A soak in time of less than 1 minute is desired.

B. Water Repellency.

Water repellency tests were run on treated soil after 6 days ageing at room temperature and again after 200 hours in the weatherometer. A large drop of water placed on the dry treated surface was observed until it soaked in or until 3 hours had passed. After 3 hours, most of the water was lost by evaporation even if it did not soak in. Such samples were designated with a plus sign in tables 1 to 3. Many of the drops maintained a high contact angle on the surface throughout the 3-hour period.

C. Rain Erosion.

Fifty drops of water were released (1 drop/sec) from a height of 2 m to fall on the treated soil. Surface spalling or deep cratering was observed in the absence of resinous binders. All of the latex binders protected the soil completely by this test.

D. Impact Resistance.

Mechanical strengths of the treated patties were compared by dropping an 8.5 g steel ball bearing from increasing heights on the patty, which was supported by a 2-in ring, until the sample broke. Duplicate samples were tested before and after exposure in the weatherometer.

E. Weather Resistance.

Treated patties were removed from the aluminum dishes and exposed on a vertical board backing in a carbon-arc unfiltered weatherometer. The samples were observed periodically for spalling or crumbling. Those that retained their integrity were reweighed after 200 hours exposure and reported as a percentage of retained weight. The exposed samples were then tested again for water repellency (on the top surface) and for falling-ball impact resistance. Impact resistance sometimes improved with exposure, but water repellency generally was decreased by exposure. Better samples retained esentially all of their original weight. Only materials that passed tests A-D were exposed to weathering tests.

MATERIALS

Polymer Binders

Commercial latex polymers are listed as described generically in supplier data sheets, but detailed compositions are not disclosed. Differences in copolymer compositions, molecular weights, presence of carboxylic monomers, nature of emulsifying agent, etc., may be more important in determining wet-out than the generic polymer type.

Polymer type	Trade name	Supplier
PVAc	Elvacet 81-900	DuPont
E/VAc	Elvace	DuPont
VAc Copolymer	Aircoflex 510	Airco
VAc Copolymer	Polyco 804 PL	Borden
Acrylic	Rhoplex AC-35	Rohm & Haas
Butyl	BP-100	Enjay (Exxon)
Urethane	5 HS	Millmaster Onyx
Saran	DL 464	Dow
Silicone Rubber	XEC 42118	Dow Corning
SBR [1]	M-145	Dowell
SBR (55 percent styrene)	DL 233	Dow
SBR	DL 234	Dow
SBR	DL 305	Dow
SBR	DL 636	Dow
SBR	DL 880	Dow
SBR (45 percent styrene)	Goodrite 2570X1	Goodrich
SBR (25 percent styrene)	Goodrite 2570X15	Goodrich

[1] Styrene-butadiene resin.

Water Repellents

Among the many water repellents that were considered, the following materials were tested more thoroughly because of their commercial availability:

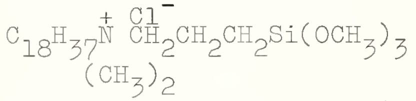
Stearic acid Na^+ salt in 50 percent aqueous isopropanol.

Stearic acid K^+ salt in 20 percent aqueous ethanol.

Dimer acid (Empol 1014, Emery) Na^+ salt in water.

Dimer acid emulsion (10 percent Na^+ neutralized) in water.

Octadecylsuccinic acid bis-Na^+ salt in water.



$C_{18}H_{37}\overset{+}{N}\underset{(CH_3)_2}{\overset{Cl^-}{CH_2}}CH_2CH_2Si(OCH_3)_3$ in water (XZ-2-2300, Dow Corning).

Sodium methylsiliconate (DC 772, Dow Corning).

Silicone fluid emulsion (XEF 4 3543, Dow Corning). An anionic emulsion of a dimethylsiloxane fluid having a viscosity of 75 centistokes.

Silicone cyclics emulsion. An anionic emulsion of mixed dimethylcyclosiloxanes of low molecular weight.

TEST RESULTS

Amount of Water Repellent

Three types of water repellents were first tested at different levels in the acrylic latex, Rhoplex AC-35. Water repellent in water was mixed with 10 ml of 3 percent acrylic latex in water to give 13 ml of 3 percent dispersion for treatment of 50 g of soil. An all-silicone fluid emulsion and an all-silicone rubber emulsion were included for comparison (table 1). As little as 1.5 parts water repellent per 10 parts of resin was enough to impart good initial repellency. All samples with an acrylic binder had good erosion resistance. The silicone emulsion was the best additive to the acrylic latex for retention of properties after exposure to weathering. No further improvement could be observed by increasing the ratio of silicone to acrylic to more than 3:10.

It seems very strange that the emulsified silicone fluid, by itself--without the acrylic latex--was not an effective water repellent. The silicone rubber emulsion was a good water repellent, but not a very effective binder. The silicone apparently must be a high polymer, or on the surface of a high-polymer resin particle to be effective as a water repellent.

Which Water Repellent?

Additional water repellents were compared with 3 parts of the silicone fluid emulsion per 10 parts of acrylic latex (table 2). Soaps of long-chain fatty acids contribute good water repellency, but are difficult to handle because of high viscosities of their solutions. The octadecyl succinic acid (bis-Na^+ soap) solution handled well, but was less effective as a water repellent. An emulsified dimer acid was much less effective than the sodium soap solution, suggesting that the emulsified material did not disperse well on the soil particle surfaces.

An emulsion of low molecular weight silicone cyclics contributed good water repellency to the acrylic treatment, but lost almost all hydrophobing action during weathering. Their volatility was probably sufficient to allow escape from the surface.

TABLE 1.--Levels of water repellent in acrylic latex, Rhoplex AC-35

Water repellent added		Tests on Granite Reef soil					
Type	Level	A	B	D	E	E-B	E-D
	Phr 1/	Seconds	Hours	Inches	Pct.	Hours	Inches
None (acrylic latex alone)		40	0.1	44	97	0.2	29
Sodium methyl-siliconate	3	25	2.5	51	100	.1	29
	15	40	3+	44	100	.2	44
	30	60	3+	44	99	1.5	29
Octadecyl quaternary silane	3	40	2.8	51	96	.1	29
	15	35	3+	-	65	.2	14
	30	20	3+	51	82	1.6	14
Silicone fluid emulsion	3	40	2.5	51	100	.1	44
	15	40	3+	44	100	2.5	29
	30	35	3+	35	98	3+	35
	90	45	3+	-	99	3+	29
No acrylic latex: (all silicone)							
Fluid emulsion	-	40	.1	(2)	(2)	-	-
Rubber emulsion	-	60	3+	21	98	3+	21

1/ Parts per hundred of resin.

2/ Patty fell apart.

Concentrated solustions of sodium methylsiliconate cause coagulation when added to most polymer latexes. Mixtures with latex could be prepared by diluting sodium methylsiliconate with the major portion of water before adding the latex. The resulting mixture was a good water repellent binder for Granite Reef soil, but lost much of its repellency after weathering.

Which Latex Binder?

Mixtures of 30 parts per hundred of resin of silicone emulsion (XEF-4-3543) in various latex binders at 3 percent total solids were poured (13 ml) over 50 g of Granite Reef soil and tested as described for soil binding and water repellency (table 3).

All latex polymers provided enough binding action to protect the patties completely against water erosion in test C, but they differ significantly in strength imparted to the patties.

The urethane latex and a polyvinylacetate latex were completely unsuited because of very slow wet-out of the soil. Other latex samples (for example, M-145) contained such high levels of wetting agent that the mixture did not impart water repellency.

TABLE 2.--Various water repellents in acrylic latex, Rhoplex AC-35 /30 parts per hundred of resin of water repellent, total 3 percent in water/

Water repellent	Tests on Granite Reef soil					
	A	B	D	E	E-B	E-D
	Seconds	Hours	Inches	Pct.	Hours	Inches
Stearic acid Na^+	<1,000	3+	30			
Stearic acid K^+	175	3+	30			
Dimer acid $2Na^+$ (solution)	90	3+	29	98	0.1	44
Dimer acid (emulsion)	60	2.0	44			
$C_{18}H_{37}$succinic 2 Na^+	21	2.5	51	-	-	-
$C_{18}H_{37}$quaternary silane	22	3+	51	82	1.5	14
Sodium methylsiliconate	30	3+	44	99	.8	29
Silicone cyclics emulsion	60	3+	37	90	.1	29
Silicone fluid emulsion	35	3+	35	98	3+	35

TABLE 3.--Silicone emulsion in various latex polymers /30 phr of silicone, total 3 percent solids in water/

Polymer type	Latex name	Tests on Granite Reef soil					
		A	B	D	E	E-B	E-D
		Seconds	Hours	Inches	Pct.	Hours	Inches
PVAc	Elvacet 81-900	300	0.75	14	70	0.15	-
E/VAc	Elvace	180	2.0	30			
VAc Copol.	Aircoflex 510	54	.25	60			
VAc Copol.	Polyco 804PL	80	2.5	30			
Acrylic	Rhoplex AC-35	35	3+	35	98	3+	35
Butyl	BP-100	55	2.5	30			
Urethane	5HS	>1,000	-	-	-	-	-
Saran	DL 464	50	2.0	29	98	3+	29
SBR	M-145	90	.1	60	79	.5	-
SBR	DL-233	55	3+	72	99	3+	60
SBR	DL 234	60	3+	14	97	2.5	14
SBR	DL 305	65	3+	60	94	1.8	44
SBR	DL 636	70	3+	85	99	1.3	29
SBR	DL 880	70	3+	100	99	1.8	35
SBR	Goodrite 2570X1	75	2.5	80			
SBR	Goodrite 2570X15	75	3+	80			

The acrylic, the Saran, and an SBR (DL-233) latex showed best retention of strength and water repellency after weathering. The SBR imparted higher strength, and, since it is less costly than the other two preferred materials, it is the binder recommended for use with silicone emulsion in water harvesting. Some other latex might possibly perform better with other water repellents.

A 3:1 mixture of DL-233 and silicone emulsion XEF-4-3543 was stable for more than 1 year at 50-percent concentration, and lost none of its effectiveness as a water repellent soil binder. Such a mixture of SBR latex and silicone emulsion has been sampled on an experimental product, XZ-8-5079.

Efficiency and Economics

In our patty tests, the 3-percent dispersion was applied to Granite Reef soil at a rate of about 3 ml/in^2 to a depth of one-half inch. When poured into the center of a large excess of Granite Reef soil, 10 ml of the 3-percent dispersion consolidated soil to a depth of 1 inch over an area of 6 in^2. Assuming an application of 2 ml/in^2, 2,600 ml of 3-percent dispersion would be required per square yard, or about 4,000 gal/acre. At a cost of $0.25/lb. for SBR and $1/lb for silicone, the material costs of treatment will be less than $0.08/$yd^2$, or about $380/acre. Hopefully, the treatment will last for at least 3 years so that the annual cost will be one-third of the above.

CONCLUSIONS

A series of simple laboratory tests was used to screen potential soil treatments for water harvesting. A mixture of a commercial SBR latex and an emulsified silicone fluid show the most promise on the basis of cost-performance and convenience in application. The mixture or the separate silicone emulsion are available for testing in water harvesting or other applications where a water repellent soil binder is desired. The silicone emulsion, alone, is completely ineffective, but is a very effective water repellent when mixed with a suitable polymer latex.

Outdoor tests on suitable soils in semiarid climates should be run to compare this mixture of silicone and organic latex with other candidate treatments for water harvesting.

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CHEMICAL WATER HARVESTING

Remy L. A. de Jong and Thomas J. Wallace [1]

INTRODUCTION

The need to develop additional water supplies for our rapidly expanding urban areas has been widely recognized, and it does not require further documentation here. It is useful, however, to categorize the various approaches now being advocated:

(A) Transbasin diversions.

(B) More extensive ground water mining.

(C) Desalting techniques.

(D) Induced seepage.

(E) Water re-use.

(F) Water exchange.

(G) Water harvesting.

All of these approaches have their specific attractions as well as handicaps, which determine their suitability for a given problem area. In general terms, the capital-intensive aspects associated with the approaches listed above fall in one or more of the following groups:

1. Construction of water conveyance systems to transport the new supplies to the places of demand.
2. Construction of water treatments plants to render the new supplies potable.
3. Construction of local engineering works to impound or divert newly created supplies.

Although such a general listing is not an adequate basis for a cost comparison between the various approaches, it does permit the preliminary conclusion that, in terms of conventional construction costs, water harvesting appears to be a very attractive alternative, since usually only minor and unsophisticated construction is involved.

Water harvesting is one of the methods available to develop supplies where they are needed most, but, as with all methods, this development still involves some type of diversion of water. It is interesting that, whereas some other methods aim to divert water that might have been beneficially used even if no diversion had taken place, water harvesting, as well as some water re-use and induced seepage schemes, is expected to intercept only water that does not have an immediate use potential, and, therefore, the latter methods are not likely to generate opposition by parties who might be able to show that they will suffer harm.

Another aspect of interest specific to water harvesting, which develops supplies by creating and intercepting sheet flow, also known as

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[1] Principal, De Jong and Associates, and President, Transcontinental Research and Development Corporation, respectively, Tucson, Ariz.

"diffused surface flow," is that it is not likely that problems will arise about the appropriation of such new supplies, since these diffused flows are not considered to be subject to appropriation, at least in the State of Arizona.

THE MECHANICS OF CHEMICAL WATER HARVESTING

The aim of harvesting is to render the soil surface impermeable, thereby eliminating infiltration, whether it be deep percolation to the ground water reservoir, or the shallow topsoil infiltration followed by evaporation loss. This aim can be achieved chemically by treating the topsoil with additives that create a water repellent zone around each individual soil particle, resulting in a condition whereby moisture in liquid form is not allowed to penetrate the treated layer, although air and vapors will continue to be able to pass through.

At this time, it seems appropriate to stress that water harvesting under field conditions constitutes an open system, incorporating several factors that are not under strict control of the operator, in contrast to laboratory experiments. It behooves the designer of a water harvesting project to take the circumstances and the behavior of the surrounding untreated watershed into account, either by eliminating or controlling undesirable inputs, or by making allowances into the design to handle the outside factors. Specific reference is made here to cases where harvesting installations were damaged by floodwaters generated in the upstream watershed, or where impervious membranes or liners were destroyed by uplift resulting from high water tables in the immediate vicinity.

Successful application of a water harvesting scheme, especially of the type discussed in this paper, depends on a thorough understanding of the following properties:

(A) The mechanical properties of the soil that is to become the foundation of the water harvesting system. Those properties can be determined and described by means of the tools and methods of conventional soil mechanics, and no discussion is needed at this time, except for emphasizing the basic importance of this group of properties.

(B) The mechanical properties of the water harvesting system superimposed on the soil, whether this system be a plastic membrane, a multistage asphalt treatment process, or some type of paving. Some water harvesting schemes have failed because the hydrologic performance was stressed to the detriment of an investigation of the mechanical feasibility of the treatment process.

(C) The chemical properties of the additives, the water, and the soil to be treated. These properties should be mutually compatible, as well as consistent with those of the two groups mentioned previously.

EXPERIMENTAL RESULTS

The primary chemical selected for evaluation was F125. [2] A two-phase experimental investigation was implemented. In phase I, a laboratory investigation was conducted on the effect of formula 125 on the following properties of the treated soil:

(A) Swelling potential.

(B) Swelling potential rate.

(C) Swell pressure.

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[2] Chemical manufacturered by Transcontinental Research and Development Corporation, Tucson, Ariz.

(D) Infiltration rate.

(E) Capillary absorption.

(F) Compressive strength.

(G) Compressive strength after freeze-thaw.

(H) Wetting and drying.

(I) Effects of temperature extremes.

(J) Consolidation properties.

(K) Chemical durability - weatherometer.

(L) Compatibility to soil types.

(M) Significance and application limite of different concentration levels.

The results established the following technical properties of chemical F 125:

(1) Resists wetting and drying cycles.

(2) Resists freeze-thaw cycles.

(3) Resists temperatures of -32° to 250° F.

(4) Increases soil strength.

(5) Deactivates cohesive soils.

(6) Renders soils water repellent.

(7) Is odorless.

(8) Is colorless; does not change the natural color of soils.

(9) Is nonbiodegradable.

(10) Is nontoxic when cured.

(11) Requires no special equipment for application.

(12) Is adaptable to standard engineering techniques.

Phase 2, the field testing of the selected soils, was conducted utilizing panels of 4 by 4 feet on a plywood base, positioned at a 4-percent slope, as illustrated in figure 1. The panels were covered with a layer of approximately 2 inches of soil, with due care being taken that no seepage could take place between adjacent panels. The panel bases were perforated to provide dissipation of percolating water, and the downstream area of each panel was provided with a filtered catch basin to prevent eroding material from entering the collection receptacles. The area of each panel was approximately 1.40 yd^2 and the pattern of treatment was as follows:

A_1 Treatment with enzyme (1,000:1 ratio of concentration).

A_2 Treatment with F125 (44:1 ratio of concentration).

B_1 Control panel, no treatment.

B_2 Treatment with F125 (33:1 ratio of concentration).

Water was applied to the panels by means of a centralized sprinkler connected to the city of Tucson water system. The rate of water application was calibrated during each test. From calibration runs, during which a number of containers were distributed over the test panels, it appeared that satisfactory uniformity of water distribution was reached at the rate of application of one hundredth of an inch per·minute, and this rate was used during all tests of phase 2. As a further safeguard for accurate application of water, a number of tests were run by manually applying premeasured quantities of water, and this method confirmed the accuracy and reliability of the automatic system throughout the test program.

Soil for this set of experiments was taken from the streambed of the Rillito Creek in Tucson, and the size gradation curve is shown in figure 2. Each test panel was filled by pouring and spreading the soil for an approximate depth of 2 inches. The surface of the soil was lightly dressed for relative uniformity and slope; all material exceeding 1 inch in size was manually removed from the surface whereever it pro-

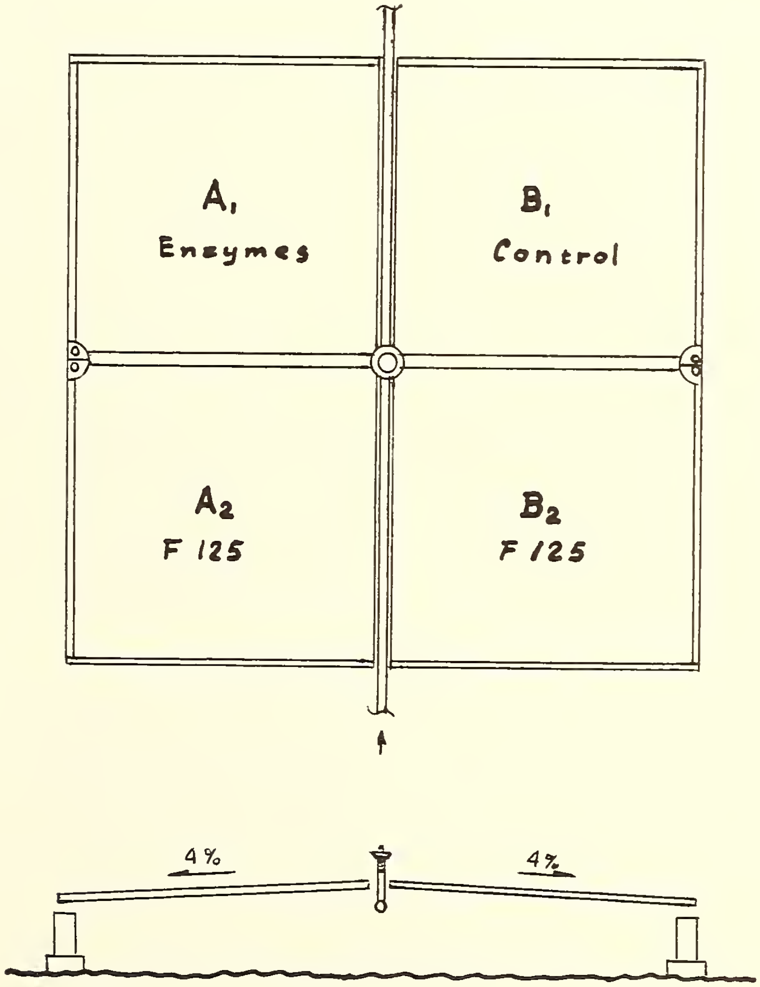
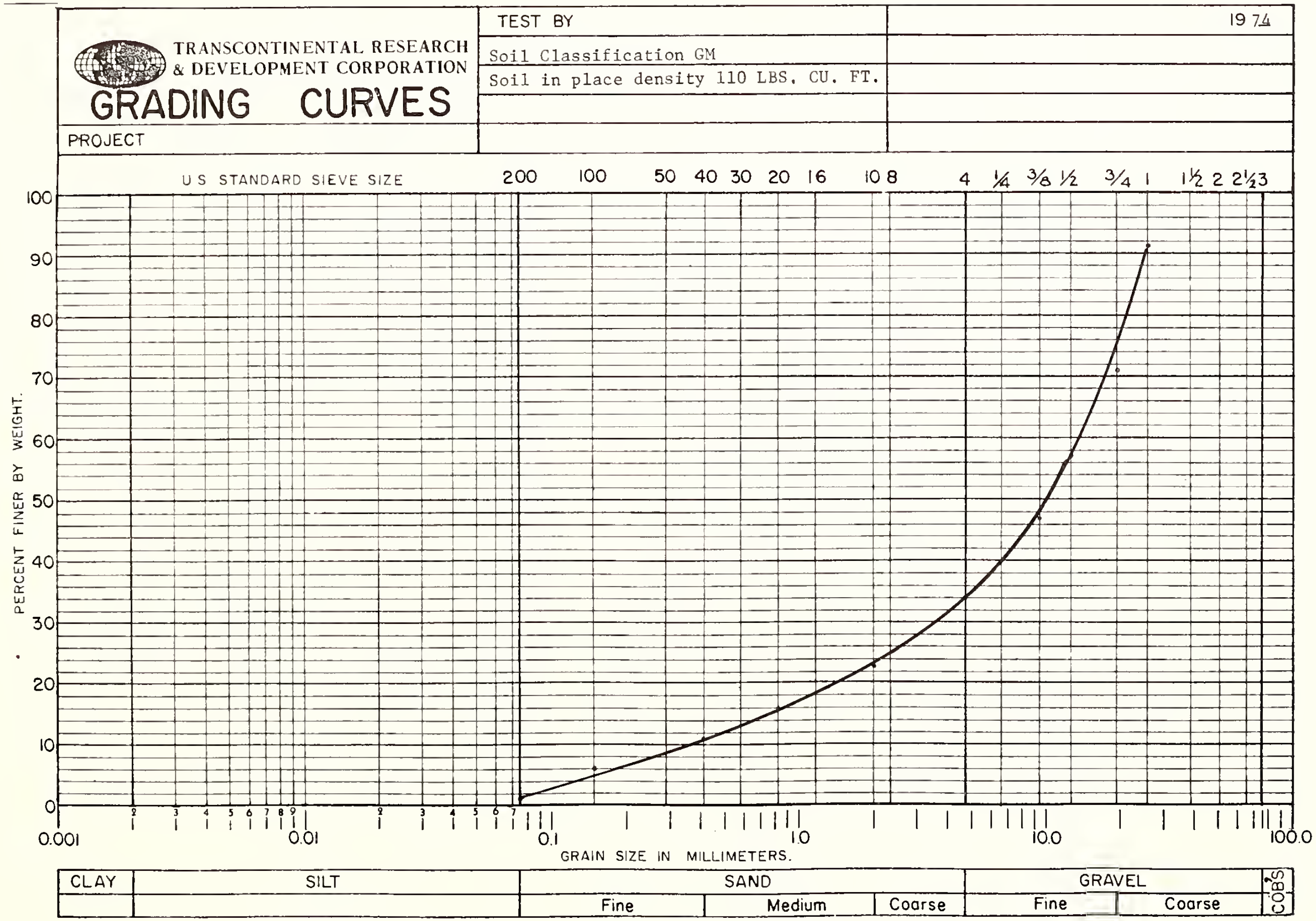


FIGURE 1.--Test panels, phase 2.



TEST BY

19 74

Soil Classification GM

Soil in place density 110 LBS. CU. FT.

FIGURE 2.--Gradation curve on water harvesting test panels.

protruded, but no effort was made to remove larger particles from the body of the soil material itself.

The durations of the test cycles for phase 2 ranged from 1 to 4 minutes. The reason for these short durations was that the primary purpose was to investigate the yield to be expected from chemical treatment under conditions of short rainfalls.

In addition, saturation periods of 1/2, 2, 4, and 6 hours were used with the object of determining the chemical capability to withstand increased and prolonged impact forces and of flood conditions. Acceleration of any trend toward erodability and the effects of the equivalent of 2 full years of rainfall were thus simulated in phase 2.

Reference should here be made to panels A_1 and B_1. The enzyme panel, A_1, was actually used to impress a point, the relationship of soils mechanics to chemicals. Enzymes have been successfully tested for seepage control (1) and have a field history of lake sealing.

The extremely granular nature of the soil precluded any effort at recorded readings for these two panels, since no period of equilibrium could be attained. The soil covers simply eroded under testing conditions. No further reference will be made to panels A_1 and B_1.

In the long run, a number of factors will determine the efficiency of chemical treatment. Among these factors are the basic nature of the soil itself (that is, fine or granular), entrained air, gas pressures, in-situ moisture, moisture content obtained from the humidity factor and subsurface soils, and temperature changes.

By spacing the experiments quite far apart in time, it is felt that a reasonable effort was made to simulate conditions ranging from complete saturation to no free-moisture content. Temperatures ranged from a low of 28° F to a high of 76°. The test site was subjected to a total of four freeze-thaw cycles.

The soil tested was a coarse, highly porous material, containing less than 2 percent fines, with a Unified Soil Classification System designation of GM (see fig. 2), and an in-place test density of 110 lb/ft^3. Note that this is an extreme test of any chemical's water harvesting capabilities.

At the conclusion of the test program, there was no recorded loss of waterproofing capabilities, nor any observable erosion of soil within the F125 test panels. The water sealing function of the chemical was 100 percent. However, due to the mechanics of the system, whereby ponding on surface irregularities occurs at lower temperatures, this water must be considered lost to evaporation; hence, at no time can a 100-percent recovery ever be accepted as a realistic figure. For these reasons, F125 has an indicated efficiency factor of 95 percent (see fig. 3).

ECONOMIC ASPECTS

As was indicated in the Introduction, the cost of developing new supplies may involve various construction activities, which need to be analyzed before the economic feasibility of a certain scheme can be established. It is ouside the scope of this discussion to attempt to compare water harvesting, chemical or otherwise, with the other approaches mentioned previously. It is, however, appropriate to present some data on the costs that might be expected on a plot of desert soil that is being prepared for chemical water harvesting. These figures may then be used for comparison with other techniques to establish feasibility and relative economy.

Let it be assumed, for illustration purposes, that a city in southern Arizona wishes to prepare a 10-acre plot, already in its possession, as a catchment area. The following cost figures may then

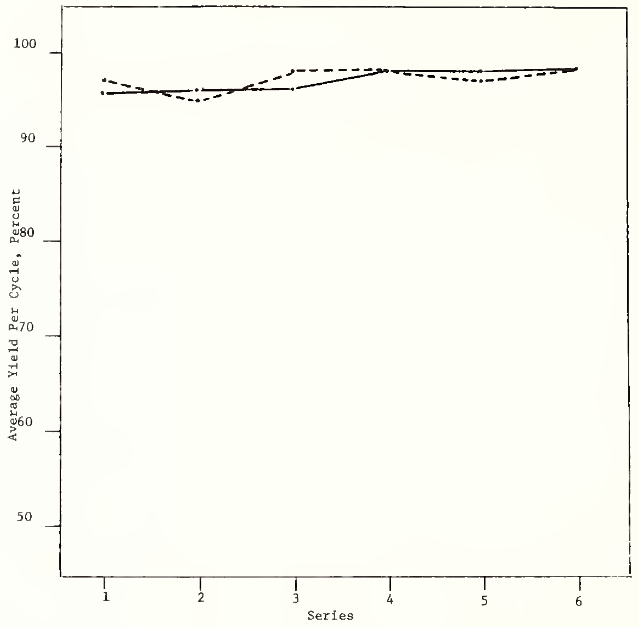


FIGURE 3.--Recovery efficiency of chemically waterproofed field test panels. (The average number of cycles per series per panel is 7.)

be used as a preliminary guide. (All calculations are based on 10 acres treated with F125 at a ratio of 44:1 and an application rate of 1 gal/yd^2.)

Materials @ 0.22/yd^2	$10,648.00
Equipment:	
1 grader No. 12 @ $140/day	70.00
1 water tank @ $75/day (1 hr)	10.00
Labor:	
1 grader operator @ $20/hr (4 hr)	80.00
1 tanker operator @ $20/hr (1 hr)	20.00
Miscellaneous expenses	50.00+
Total cost	$10,878.00+
Cost per acre	$ 1,087.80+

Let it further be assumed that the average annual precipitation in the area is 12 inches, then the total input into the 10-acre system would be 10 acre feet, or 3,223,440 gal. Also, assume that there is a 5-percent loss due to evaporation from surface irregularities and local ponding, then the annual anticipated recovery would be 3,060,268 gal. In view of the earlier mentioned cost per acre of $1087.80, which also is the cost per acre foot, the cost per gallon on the annual basis would be $0.0036.

Analysis clearly shows material cost to be the control factor. Due to the extreme nature of the conditions (66 percent gravel, and no fines; see fig. 2), this would be the anticipated maximum cost. It can further be expected that site conditions containing major proportions of silts or clays, would reduce costs by 75 percent. Cost could be still further reduced by bulk volume purchase of materials. Dependent on bulk volume purchase of materials and site conditions, the cost per harvest acre would run from less than $272 to $1,000.

In concluding this section, it should be noted that the establishing of the marginal cost of an acre foot of water is a very subjective matter. The harvesting of 1 acre has the potential to supply 1,000 head of cattle for 1 month during a period of prolonged drought; what would the cost be for the loss of these animals? Similarly, the cost of generating additional supplies in remote areas where human life and welfare are in jeopardy, should not be compared with the expense involved in relieving, to some extent, the existing pressures on our municipal water supply systems.

LEGAL ASPECTS

Individuals involved in water conservation practices should be aware of the legal frame of reference of their activities; therefore, this section will briefly review this area particularly as it applies to water harvesting in Arizona. The discussion may serve as a starting point for practitioners of other techniques, and in other States.

Arizona adheres to the appropriation doctrine where control of its waters is concerned, and it rejects the riparian doctrine. [3] The Statutes [4] provide that "...the waters of all sources, flowing in... natural channels, or in definite underground channels, whether ...flood, waste, or surface water, ...belong to the public and are subject to appropriation and beneficial use...." Appropriation of such waters is handled through the Arizona State Land Department according to criteria and procedures as spelled out in the Statutes.

The matter of direct importance to those who put into practice water conservation techniques is whether they will be entitled to use the fruits of their labors. In a fairly recent case, [5] it was determined that a landowner who had a valid appurtenant water right could not, through water saving practices, apply the water thus saved to immediately adjacent lands owned by that person. The facts involved an irrigator who, by lining his diversion canal, effectively stopped uncontrolled seepage, and as a result managed to deliver almost all of the water entering the headgate of the canal to his fields located at the downstream terminus. Although at first glance this decision appears to discourage water saving practices, it is likely that incorporating such practices into an application for appropriation would have yielded a desirable result.

How does water harvesting fit into this picture? Although the statute mentioned above declares water of all sources appropriable, it does at the same time attempt to identify those sources, and in so doing implicity excludes sheet flow, or as it is known in legal parlance "diffused surface water," from the appropriation process. In a recent case, [6] the court held that "surface waters" were not appropriable, and it further proceeded to define those "surface waters" as waters that do not follow a defined course or channel and are lost by being diffused over the ground through percolation, evaporation, or natural drainage. The court further opined that essential characteristics of "surface waters" are that they: (1) Follow no defined course, (2) are not concentrated or confined in standing bodies of water but are spread over the ground, and (3) have short-lived flows.

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[3] Arizona Constitution, Article 17, paragraph 1.

[4] Arizona Revised Statutes, paragraph 45-101.

[5] Salt River Valley Water Users' Association v. Kovacovich, (1966) 3 Arizona Appeals 28,441 P.2d 201.

[6] Espil Sheep Company v. Black Bill & Downey Parks Water Users' Association (1972) 16 Arizona Appeals 201,492 P.2d 450.

A narrow construction of the above appears to indicate that, in order to be exempt from the appropriation procedures, water harvesting systems should be set up such that the project areas do not contain identifiable channels, and the harvested waters should be collected directly in tanks or reservoirs, rather than be transported in streams or other existing water courses that would make them streamflows and thereby subject to appropriation. According to the Arizona definition of "surface waters," additional means of disposal of harvested waters might be transport through pipes or conduits, and, possibly, induced infiltration in existing stream channels.

However, in view of the vagaries involved, it appears that the most prudent approach would be to estimate in advance the amount of water to be expected from a certain water harvesting scheme, and to apply in advance to the State Land Department for permission to appropriate water harvesting yields in line with such estimates.

CONCLUSIONS

Water harvesting by chemical means appears to be a viable alternative if terrain and soil conditions are favorable, and possibilities exist to bring the costs in line with other methods under consideration.

Construction involved in site preparation and application of the chemicals require work of only average complexity and sophistication, which enhances the possibilities of application in remote areas.

Water harvesting is a multiplex consideration. By extension and with slight modifications, a shallow subsurface waterproofed chemical membrane could harvest water for in-situ crop cultivation, although no research data along this line have been collected to date.

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PERFORMANCE AND DURABILITY OF SHEET METAL, BUTYL RUBBER, ASPHALT ROOFING, AND BENTONITE FOR HARVESTING PRECIPITATION [1]

Rome H. Mickelson [2]

INTRODUCTION

Water supplies for livestock are frequently inadequate on semiarid rangelands in the central high plains region because ground water aquifers are not economically accessible or available. The problem is compounded by frequent and extended drought periods. Inefficient use of range forages and poor gains on livestock result from inadequate distribution of available watering sites (11). Farmers and ranchers have attempted to compensate for this by hauling or piping water to suitable range sites; however, the process can be costly and time consuming.

The ancient art of collecting and storing precipitation for agricultural and domestic use has been utilized to provide water supplies in some of the more arid regions of the world (5). The practice is now more commonly referred to as water harvesting and offers potential for a relatively economical and dependable source of water.

In recent years, numerous investigators have devoted their time and talents to perfecting an economical and efficient way to harvest water from natural precipitation. Two basic research techniques have been used: (1) Chemically treating the surface soil to reduce infiltration and increase runoff (1, 4, 5, 6, 7, 10) and (2) covering the soil surface with some type of impervious membrane (2, 7, 10).

The first technique has involved the use of various hydrocarbons such as fuel oil, asphaltic emulsions, latex emulsions, anionic paraffin wax emulsions, salt, and bentonite. They are generally low-cost materials but do not have the durable characteristics to sustain a high degree of water harvest efficiency without periodic maintainance. These materials may also require additional treatment of the soil surface before application to obtain a smooth surface that is relatively free of vegetation and stabilized to reduce excessive erosion.

Impervious membranes such as concrete, sheet metal, and butyl rubber provide greater durability, water harvest efficiency, and lower maintainance; however, initial costs are high. Asphalt roofing and plastic sheeting are much lower in cost and provide the same degree of efficiency but are less durable. Use of most impervious membranes does not require as much soil preparation as the chemical treatments.

Climate, soils, and topography are important factors to consider in the selection of materials for harvesting precipitation in any given area. Of these, climate is the most critical factor because the material used on the catchment area must withstand the annual variations in temperature, wind, solar radiation, and nature of precipitation. These weather conditions are highly variable between geographical regions of the country. Thus, a particular water harvest treatment may be successful in one geographical area but will not be suitable in another.

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[1] Contribution from the Central Great Plains Field Station, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Colorado State University Experiment Station.

[2] Agricultural engineer, U. S. Central Great Plains Field Station, Akron, Colo.

Asphalt compounds with and without a protective surface coating have been used more successfully in the arid southwestern United States (6) than in the semiarid area of the west central and northern Great Plains (9). Extreme variation of temperature in the Great Plains is the main factor that contributes to the rapid deterioration of asphaltic compounds. The incidence of high winds and hail are also more prevalent in the central high plains region. Catchments constructed from more durable materials are necessary in this region to withstand the changeable, versatile weather conditions.

Research on water harvesting techniques was initiated at Akron, Colo., in 1968, to test the durability and effectiveness of sheet metal, butyl rubber, and asphalt roofing membranes and a soil-bentonite mixture. This paper describes the techniques used and reports results and observations made during 1969 through 1972.

EXPERIMENTAL SITE CONDITIONS

The experimental site on the Central Great Plains Field Station near Akron is 4,535 feet above sea level on native rangeland that has never been tilled. The soil is classified as Rago silt loam and is derived mainly from eolean deposits. The subsoil, at a depth of 4 to 8 inches, grades to a clay loam with 20 to 25 percent clay, which, upon drying, contracts to form vertical prismatic aggregates. The site has a slope of about 2 percent.

Local climate is semiarid and typical of the west central Great Plains region. Average annual precipitation is 16.6 inches, with approximately 72 percent occurring in May through August. The area receives an annual snowfall of about 31 inches. Temperatures are highly variable and can range from a minimum of -29° F in January to 107° in July. The mean daily minimum temperatures vary from 8° in January to a mean maximum daily temperature of 80° in July. Mean daily windspeed ranges from 5.6 miles per hour during August to 8.4 mi/h during April. Open-pan evaporation averages about 66 inches per year over a 7-month period beginning in April. Solar radiation is relatively high and ranges from 194 langleys per day in December to 614 langleys per day in June. Solar radiation of over 700 langleys per day is not uncommon during the summer.

EXPERIMENTAL PROCEDURE

Ten plots, 20 feet wide and 100 feet long, were oriented to obtain uniform 2-percent slopes. The plot areas of all treatments, with the exception of the check, were worked lightly with tandem disk to remove sod clumps and obtain a relatively smooth surface. The five treatments consisted of sheet metal, butyl rubber, asphalt roofing, soil-bentonite mixture, and native short grass check. Treatments were replicated twice and randomly located. One replication had a southern exposure and the other a western exposure.

The sheet metal was available in 3- by 5-foot galvanized sheets. Beginning at the lower end, each sheet was laid overlapping one another 1 to 2 inches. The joints were caulked and riveted. Plot borders 6 inches high were formed by bending ends of outer metal sheets 90 degrees to vertical position. A berm of soil was thrown up along the outside of the plot to anchor the membrane.

The butyl rubber sheeting was commercially obtained in 20- by 50-foot sheets, which were spread across the plot by hand. The edges were initially tacked to elevated boards anchored in the soil. This later proved to be a failure when high winds dislodged the sheeting. The plot area had to be reduced to allow enough border to lap over an elevated berm and be buried in the soil along plot edges. This has since completely alleviated any problems associated with high winds.

The asphalt roofing was available in rolls 3 feet wide. The sheeting was sealed with asphalt cement and tacked to 1- by 4-inch boards at all overlapped seams. The boards were pressed into the soil the width of the board so that the sheeting lay flush on the soil surface. Plot borders were formed by tacking the sheet edgings to elevated boards that were anchored in the soil.

The bentonite treatment consisted of applying and mixing approximately 4.5 tons bentonite and 4 pounds atrazine per acre in the top 2 inches of loose soil. A layer of pea-size gravel was spread on the surface. The entire plot was packed with heavy roller to obtain a smooth sloping surface. The check plot consisted of undisturbed native sod.

The lowest corner of each plot was equipped with entrance boxes and 90-degree, V-notch weirs, which were made from 3/8-inch aluminum sheeting and calibrated in a hydraulics laboratory. Rating curves were determined and water-stage recorders installed. The runoff was calculated from hydrographs of flow through the V-notch weir and reported in volume per unit area because the butyl rubber catchments were reduced in size following wind damage in 1970. Runoff was not stored or analyzed for sediment content. Two standard rain gages and a recording rain gage were located in the experimental area to measure precipitation.

From 1969 to 1972, measurements were taken each year over a 6-month period beginning in April. Analysis of variance and Duncan's Multiple Range Test was applied to total runoff for each treatment. Significant difference was determined at the 5-percent level. Correlations between storm rainfall and runoff and between mean monthly rainfall intensity and water harvest efficiencies were made for each treatment.

EXPERIMENTAL RESULTS

Monthly precipitation over a 6-month period for 1969-72 is given in table 1. The 6-month total represents 80 percent of the annual precipitation for the area. The mean 6-month total precipitation over the 4-year period was 2.2 inches below the long term average. All years had below normal amounts, and 1970 was the driest year. Approximately 40 storm events of 0.01 inch or more occurred each year. Storm characteristics of rainfall varied with time of year. Rainfall during the spring occurred from low intensity storms. During the summer months, rainfall increased in intensity, reaching peak intensities during July. Storm intensities decreased in August and September. Incidence of hail is high in the area; however, no severe hail occurred during the reported test period.

The volume of water harvested in summarized in table 2.

The technique for measuring water harvested does not provide an accurate determination of runoff at low flows that result from low intensity storms. Most of the error in volume determinations occurred in the recession portion of the hydrograph, particularly from the impervious membrane catchments. However, since the same measuring devices were used on all plots, reasonable interpretations can be made from relative differences due to treatment effects.

TABLE 1.--Precipitation for April through September at the water harvest site on the Central Great Plains Field Station near Akron, Colo. (1969-72)

	Inches of precipitation					
Month	1969	1970	1971	1972	4-yr avg.	Long term mean 1/
April	0.73	0.87	2.47	0.92	1.25	1.77
May	4.02	2.23	2.80	2.28	2.83	2.98
June	2.31	3.25	1.29	1.80	2.16	2.54
July	2.78	1.85	2.07	2.94	2.41	2.69
August	.45	.44	1.25	3.63	1.44	1.96
September	1.14	.85	2.08	.10	1.04	1.38
Total	11.43	9.49	11.96	11.67	11.13	13.32
No. of storms	35	32	55	43	41	- - -
Mean storm intensity 2/	0.26	0.20	0.19	0.32	0.24	- - -

1/ Monthly mean precipitation over 66-year period at the Central Great Plains Field Station.

2/ Storm rainfall intensity in inches per hour.

TABLE 2.--Mean total monthly volume of water harvested per unit area from 5 surface treatments over a 4-year period at Akron, Colo.

	Runoff in gallons per square yard					
Month	Sheet Metal	Butyl Rubber	Asphalt Roofing	Bentonite	Grass Check	Potential
April	3.40	2.68	3.07	0.0	0.0	7.01
May	9.13	7.79	8.17	2.25	.74	15.88
June	6.82	6.79	6.73	1.90	.61	12.12
July	8.89	8.87	8.34	5.33	1.72	13.52
August	4.82	6.33	3.77	1.91	.04	8.08
September	2.52	2.50	2.22	.44	.06	5.84
Total 1/	35.58a	34.96a	32.30a	11.83b	3.17b	62.45
Efficiency 2/	56.9	56.0	51.7	18.9	5.1	100

1/ Means among treatments with same letter are not significant at the 5-percent level.

2/ Percentage of precipitation that results in runoff from the catchments.

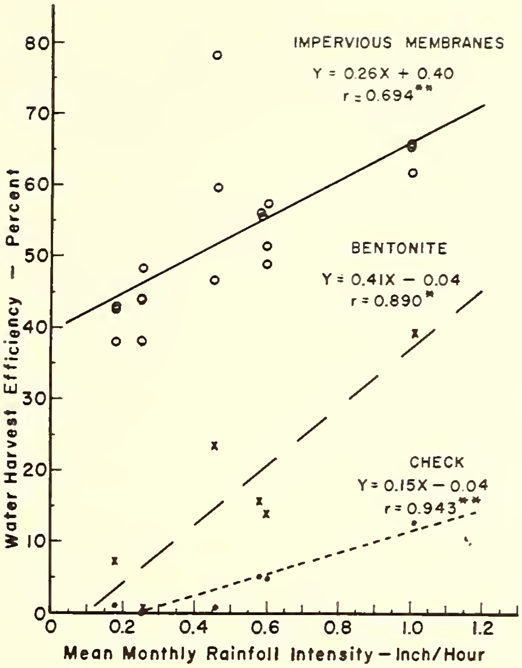

FIGURE 1.--Relationship showing effect of rainfall intensity on water harvest efficiency of different treatments. (* = 1-percent level of significance; ** = 5-percent level of significance.)

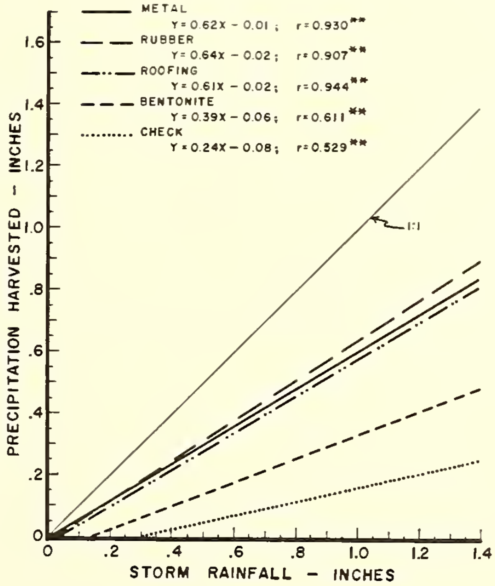

FIGURE 2.--Relationship between storm rainfall and precipitation harvested from 5 different treatments.

Treatment Effects

The monthly volume of water harvested from any given treatment was related to the monthly precipitation. Average annual volume of water harvested from the impervious catchments (sheet metal, butyl rubber, and asphalt roofing) were significantly different than that harvested from the soil-treated catchments (bentonite and check). The butyl rubber and sheet metal catchments have yielded similar amounts of runoff every year. The asphalt roofing was comparable in amount of water harvested to both the sheet metal and butyl rubber plots the first year, but annual amounts have since tended to decrease with time. Water harvested from the bentonite treatment was almost four times the amount from the check plot. The difference in mean of total period values between the bentonite and check treatments was only 0.04 gallons per square yard from being statistically significant at the 5 percent level.

Water harvest efficiency is the percentage of precipitation that results in runoff. Values of 56 percent were obtained from the sheet metal and butyl rubber treatments (table 2). The asphalt roofing treatment harvested 52 percent. Bentonite reduced infiltration, to some extent, as 19 percent of the precipitation was harvested compared with 5 percent from the check plot. The efficiency was considerably lower than the 95 to 100 percent expected from the impervious membrane catchments. Previous discussion alluded to the difficulty of accurately measuring low or trickle flows through V-notch weirs on the impervious treatments. This was not so much the case on flows from the bentonite and check treatments because the recession portions of the hydrographs from these treatments were more abrupt.

Water harvesting efficiencies were affected by intensity of rainfall. The impervious membrane catchments have yielded up to 80 percent of the precipitation from individual short duration, high intensity storms during the summer months. The efficiency decreased from the low intensity storms, which are more prevalent during the spring and fall seasons. A general relationship between storm intensity and water harvest efficiency is shown in figure 1. Mean monthly values were used to illustrate the relationship. The impervious membrane treatments showed similar relationships and, therefore, were grouped together. Though a general trend is shown, the degree of efficiency response to storm intensity was not as great from the impervious membranes as that from the bentonite treatment. Correlations showed that, for the bentonite treatment, 79 percent of the variation was due to storm intensity compared with 48 percent for the impervious membrane treatments. The check treatment showed least response to storm intensity; however, 89 percent of the variation in water harvest efficiency was due to storm intensity. The correlation was statistically significant at the 1-percent level for the membrane and check treatments and at the 5-percent level for the bentonite treatment.

Rainfall-Runoff Relationships

Regression analysis was made on rainfall-runoff relationships of all individual storm events yielding runoff over the 4-year period. The relationships are graphically illustrated in figure 2. More than 145 events were included in the analysis for the impervious membrane treatments. The bentonite and check treatments had 47 and 18 runoff events, respectively.

The rainfall-runoff relationships for the impervious treatments were similar. More than 80 percent of the variation in runoff could be attributed to storm rainfall. Regression coefficients for sheet metal, butyl rubber, and asphalt roofing were 0.6 inch of runoff per inch of rainfall.

Response of runoff to rainfall from the bentonite was less than that from the impervious membrane treatments, but more than that from the check treatment. Runoff increased 0.39 inch from every inch of rainfall with a correlation coefficient of 61 percent whereas the check plot yielded 0.24 inch runoff per inch of rainfall with a correlation coefficient of 53 percent. All correlation coefficients were significant at the 1-percent level.

Runoff threshold, or amount of rainfall necessary to produce the first increment of runoff, varied for most treatments. The runoff threshold for sheet metal and butyl rubber has been consistently 0.01 and 0.02 inch, respectively. That for the asphalt roofing has been 0.03 inch, but this threshold is increasing with the gradual deterioration of the asphalt roofing surface. The runoff threshold for the bentonite and check varied with frequency and intensity of rainfall, but has averaged 0.15 and 0.33 inch, respectively.

Annual water harvest efficiencies vary from year to year, depending on the frequency and intensity of rainfall. Figure 3 provides a graphic illustration of how annual water harvest efficiency of each treatment has changed over the 4-year period. With the exception of 1970, when wind damaged the butyl rubber plots, both the sheet metal and butyl rubber membranes have similar efficiencies. They were as effective in 1972 as in 1969 when installed. Water harvest efficiency for the asphalt roofing was as high as that of the sheet metal and butyl rubber during the first 2 years but has since shown a tendency to decrease due to deterioration of the asphalt. The variation in water harvest efficiency for the bentonite and check treatments is primarily due to the frequency and intensity of storms. Vegetation is gradually reoccurring on the bentonite treatment. However, it has not appeared to effect any significant changes in water harvest ability. No efforts have been made to curtail the growth of vegetation on the bentonite plots. The grass on the check plots has not materially changed since the experiment began.

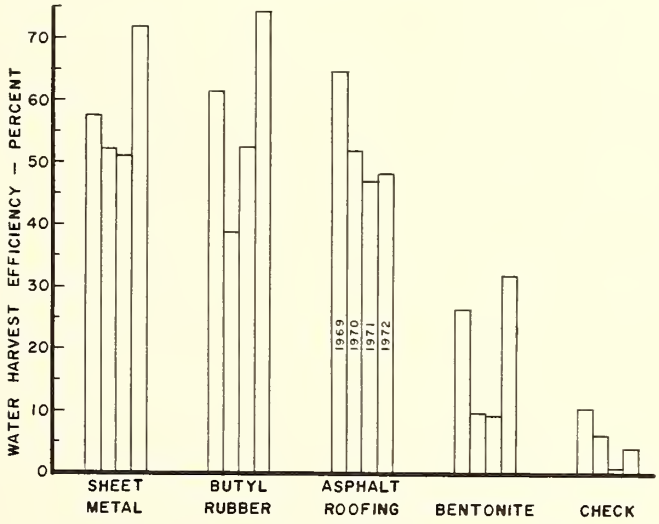

FIGURE 3.--Annual variation in water harvest efficiency for 5 different treatments (1969-72).

Durability Characteristics

Any material used in building water harvesting catchments has to endure freezing and thawing, wetting and drying, solar radiation, wind, and hail. Sheet metal, though expensive, has shown to be rather resistant to all weather conditions. It should be galvanized or treated to prevent corrosion. Sheet metal, as well as other impervious membranes, must be securely anchored to prevent damage by wind.

The sheet metal plot with a south exposure has been uplifted twice by strong winds. In both occurrences, northerly wind gusts reached 45 to 55 mi/h. The sheet metal plot with a west exposure was not affected in either windstorm. This would tend to indicate that some consideration might be given to avoid locating catchments on areas with abruptly changing slopes leeward and downhill from the strongest prevailing wind direction.

The butyl rubber has not shown any evidence of deterioration, but the membrane has not been subjected to a severe hailstorm. Extra care is necessary to properly bury and cover the edges of the membrane so that rodents cannot burrow under the membrane edges. This was the reason for failure following the initial laying of the membrane. Once holes are made by rodents, subsequent high winds can dislodge the entire membrane.

Asphalt roofing is an economical membrane for use on catchments, but its long term effectiveness is questionable without periodic maintainance. The asphalt became soft and pliable under high temperatures. In this condition, the membrane was easily punctured by rabbits and windblown large tumbleweeds crossing the plots. Though the membrane was laid flush on the surface, soil has not provided a firm base. If the membrane were laid on a solid platform, such as that provided for on building roofs, the material would presumably have a longer effective life. Numerous small cracks developed in the membrane wherever the asphalt roofing came in contact with the soil, but not where it came in contact with the boards underlying the seams. When open cracks and holes occur, water leaks through and vegetation soon emerges. Construction costs would increase substantially if some type of firm base were necessary to support asphalt roofing.

The bentonite treatment yielded more runoff than the untreated grass check. Presumably, the increase was due to reduced infiltration, but part could be attributed to removal of vegetation. Herbicide (atrazine) was applied to temporarily curtail all vegetative growth. A herbicide would not be practical for use on water harvesting catchments when the intended use is for livestock water supplies. The herbicide is apparently deteriorating because some vegetation is reoccurring. It is a matter of time as to how fast the catchment area will be completely vegetated a and what effects, if any, vegetation will have on runoff.

The check plots contain primarily the short, warm growing season grasses, which are drought tolerant. They have not changed in consistency or species for years. The grass has never been subjected to grazing or clipping.

Water Quality

No attempt was made to analyze the quality of water from the catchments. Some indication of sediment content was made by observing the sediment deposited in the entrance boxes to the weirs. The boxes were cleaned once each year at the beginning of the runoff season. Entrance boxes below the sheet metal usually contained very little sediment. The butyl rubber and asphalt roofing plots had more sediment in the entrance boxes. Most of the sediment on the impervious membrane treatments originated from deposition of windborne dust or fine soil.

The bentonite and check plots had more sediment deposition in the entrance boxes than did all other treatments. However, there did not appear to be much difference in sediment content between the bentonite and check treatments. The compacted layer of pea-sized gravel on the bentonite treatment was effective in reducing plot erosion. Consideration is being given to installing collection tanks below the entrances on one replication to determine both quality and quantity of the runoff water. The quantity will be compared with that determined from the runoff hydrograph and any consistent error resulting from the comparison would be used to correct previous runoff records.

CONCLUSIONS

Durability, cost, performance efficiency, topography, and soil type are important factors for consideration in any design of an effective water harvesting catchment. The practice can provide an economical source of good quality water. A major deterant to using the practice has been costs.

Surface membranes that are known to have durable characteristics are expensive. However, excluding concrete, surface membranes do not require much time and labor on preliminary soil preparation such as smoothing or leveling. Any soil preparation can be eliminated if suitable sites for catchments are carefully selected. Impervious membranes may be constructed on any slope with the same degree of expected efficiency.

Chemically treated soils for water harvesting catchments consist of less expensive materials for construction, but more time and labor is required both in preliminary preparations of the soil surface and treatment. The water harvest efficiency of these treatments may be increased by constructing catchments on steeper slopes than normally used provided precautionary measures are utilized to control erosion.

No attempt was made to make an economical appraisal of the treatments described in this paper because of the suspected error in runoff measurement as mentioned under "Treatment Effects." An evaluation will be made following further investigations on the measuring technique. Such an evaluation will not only include cost of materials, depreciation, and interest on investment but time and labor as well.

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DISCUSSION

SESSION II, Part 1--Sol Resnick, Chairman

G. WILLIAMS: Does the use of oil or bitumen aprons yield tainted or or odorous water that would make the water unsuitable for livestock use?

I. LAING: They did get discoloration and oil slick from these catchments, and tests were made, but at present there are no recognizable chemicals or unuseable effects.

SESSION II, Part 2--Sol Resnick, Chairman

WATER HARVESTING CATCHMENTS ON INDIAN LANDS IN THE SOUTHWEST

Joseph V. Chiarella and William H. Beck [1]

INTRODUCTION

In the Phoenix Area of the Bureau of Indian Affairs (BIA), 32 catchments have been constructed. The earliest one was built in the 1930's at Shungopovi on Second Mesa of the Hopi Reservation. The rest of the catchments have been constructed since 1957.

The structures were built in different physiographic regions varying from the semidesert of southern Arizona to the sub-Alpine zone in northeastern Utah. These vegetative zones vary respectively from extremely high summer temperatures of 120° F to the frigid below 0° range and from an annual rainfall of 5 inches to better than 30 inches of precipitation. In Arizona, the catchments are scattered over areas ranging in elevation from 1,500 to 6,500 feet.

A few of these catchments, such as the one at Shungopovi, used the native terrain in their construction without too much disturbance of the natural topography or vegetation. However, if the catchment site needed special preparation, the general procedure was to remove the vegetation and smooth the ground to an even gentle slope. Generally, the site is then treated with a soil sterilant, usually polyborchlorate, to prevent plant regrowth. The catchment itself is then constructed using the specific material to accomplish the purpose desired.

With this brief introduction, we will discuss the catchments that have been constructed on the reservations in the Southwest.

FORT APACHE RESERVATION

Five catchments were constructed on the Fort Apache Reservation. All of these involved various materials in their construction.

Flying V or Bonehead Catchment

This catchment was originally constructed in 1960, using a standard Arizona Highway Department oil and gravel cold patching mix. The mix was spread out in a 4-inch layer by a road grader and rolled with loaded, dual-wheeled dump trucks for compaction. The size of this catchment was 10,000 ft^2 on about an 11 percent slope. At the end of the first year, this structure was beginning to crack and breakup at the upper end. At the lower end near the outlet, there was some buckling and some heaving.

In 1962, a cationic asphalt seal coat was applied by pouring the asphalt from 50-gal drums and swabbing it over the surface with mops. This work was done with the cooperation and assistance of the U.S. Water Conservation Laboratory in Phoenix.

Since 1962, no further major rehabilitation work was done on this catchment: Vegetation was cleared from the surface several times. Regrowth has not been profuse nor is it a major problem. This catchment has furnished stock water since its initial construction.

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[1] Area Range Conservationist, Phoenix Area Office, Phoenix, Ariz. and Supervisory Range Convervationist, Truxton Canon Agency, Valentine, Ariz., respectively, Bureau of Indian Affairs.

Cedar Mesa Catchment

A paved catchment of soil cement 10,000 ft^2 was completed in September 1961. The soil was treated with 10 percent by volume of Portland cement to a depth of 4 inches. It was mixed with a tandem disk harrow with water being added as it was disked. A dump truck was used for compaction. The pavement was covered with building paper for 5 to 7 days.

Approximately 2 months after completion, the soil cement was checking, appeared to be porous, and could absorb moisture. The crumbling surface was swept off with hand brooms once or twice. It continued to crumble and crack.

In the summer of 1962, the deteriorating surface was sprayed with an asphalt-diesel fuel mixture. This was done with the cooperation of the U.S. Water Conservation Laboratory which furnished the asphalt, the equipment to apply it, and assistance in the treatment. The soil cement continued to crumble beneath the asphalt.

The soil cement and asphalt was completely removed in the fall of 1963. The surface was then sprayed with asphalt, and a Tedlar film (polyvinyl fluoride) was rolled out over this surface. The overlap between the strips of Tedlar was bonded with asphalt. This project was accomplished in conjunction with the U.S. Water Conservation Laboratory which furnished the spray equipment, the materials used, and the technical assistance.

The Tedlar was continually tearing and ripping, requiring constant repair. This was accomplished by using cut Tedlar patches and bonding them to the surface with asphalt. By 1967, the Tedlar proved to be inadequate and was removed.

A rapid-setting cationic asphalt emulsion, type RS-3KH, was sprayed on the bared surface at the rate of 0.5 gal/$yd.^2$ Phillips' polypropylene (Petromat) sheeting in 6- and 15-foot widths was rolled on the surface and then covered by spraying with the same emulsion at the same rate. Sand was then scattered by hand over the fresh asphalt-polypropylene [2] surface.

Deterioration of polypropylene in uncovered spots was noted in the spring of 1968. The Phillips Petroleum Company treated the surface with six drums of Battenfield Cutback mixed with Johns Manville 7M-02 asbestos. This material was mixed by hand in drums, poured on the surface, and mopped to cover it. Since this treatment, there has been no further breakdown of the fabric. The original decomposition was due to an insufficient asphalt covering, which allowed ultraviolet radiation to attack the fabric.

Metate Catchment

This catchment is 50 feet wide by 200 feet long with an earthen pit-type tank located at the lower end of it. The original treatment consisted of spraying a low viscosity, rapid curing asphalt (RC-Special) on rain-moistened soil in the spring of 1963. The soil cracked upon drying, so in the summer of 1963, a seal coat of SS-2B, a slow setting, anionic emulsion modified by the addition of 3 percent butyl latex by weight, was applied. However, the cracking continued and the pavement disintegrated (1). This work was done in cooperation with the U.S. Water Conservation Laboratory at Phoenix.

In the spring of 1964, this catchment was disked and rolled. The surface was sprayed with MC-250, a medium-cure cutback made from soft asphalt. This was covered with 1.5-mil-thick black polyethelene film (1).

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[2] Polypropylene is manufactured by several companies under trade names like Petromat, Ozite, Herculon, and others. It is used for outdoor-indoor carpeting and furniture fabric coverings.

At the same time, the storage pit was sprayed with asphalt and covered with fiberglass and then resprayed with asphalt. Again, this work was done in cooperation with and under the supervision of the U.S. Water Conservation Laboratory. By the summer of 1965, the polyethylene had deteriorated. The catchment surface was rolled with a vibrating roller and then sprayed with asphalt and covered with 2-mil polyethylene sheeting. At the same time, the storage pit was sprayed twice with asphalt and then given a final coat of a clay emulsion.

Holes appeared on the polyethylene surface from sharp stones beneath. Some tearing of the polyethylene by wind also occurred. In the spring of 1968, the catchment was sprayed lightly with SS-2H anionic asphalt emulsion. This was then covered with 3/4-oz fiberglass matting rolled on by hand. Approximately 85 percent of the matting was then sprayed with SS-2H, whereas the remaining 15 percent was sprayed a year later.

Mescal Pit Catchment

In 1965, this area was covered with Dow-Chlorinated Polyethylene, 48 inches wide and 0.020 inch thich. The strips were bonded together with xylene sprayed on with a portable hand sprayer, making a 3-inch-wide seam. Outside of the initial treatment, only routine maintenance has been performed such as plant removal and patching of holes in the polyethylene where vegetation came through it or where rodents chewed on it.

Gleason Flat Catchment

This catchment was constructed in the summer of 1968 of 12 to 16 gage, 4- by 12-foot aluminum sheeting nailed to a wood frame of 2- by 8-inch pine lumber. Several problems were encountered in a very short time. Inexperienced local workers built the structure with little planning and no consultation with others in BIA or from the U.S. Water Conservation Laboratory, who already learned by previous faulty procedures. Roots of oak, beargrass, and other plants sprouted causing undulations in the surface and separation between the sheeting and the ground.

HOPI RESERVATION

Four catchments were built on the Hopi Reservation over the years, including the previously mentioned one at Shungopovi. All of these catchments have been abandoned for reasons herein enumerated.

Shungopovi Catchment

This catchment is the oldest one of which we have records in the Bureau, although the Indians have used the same principle for many hundreds of years. It is one of the few constructed on a site almost undisturbed of its native edaphic environment.

The village of Shungopovi is located high up on Second Mesa. The village itself is built on sandstone rock. In the early 1930's, the people decided to store rainwater when possible for their use rather than carrying it up from the valley several miles away. An area several hundred feet square was set aside and fenced. Below this area, they dug and hewed a deep cistern in the rock. This was covered with a concrete roof with openings left for the water from the sandstone rock area above to drain into it. As recently as 6 years ago, this catchment was still functioning. At that time, a community well and water system was put in by the Public Health Service. While this cistern system was far from meeting the lowest sanitation requirements, it played an important part in supplementing the village water supply. This was especially true back in the days when water had to be hauled to the village on the backs of burros.

Burro Springs Catchment

This catchment, 96 by 174 feet in size, was constructed in 1959. It was located on top of a small butte. It was made of 1/2-inch Hydromat, 4- by 12-foot asphalt impregnated sheets. These sheets were shingled and bonded together with asphaltic mastic. From completion in August 1959 until March 1963, the tank at the site had water in it continually. In March 1963, high winds lifted the surface, tearing the covering into many pieces.

The remaining Hydromat covering was removed from this site, and in the fall of 1963, two base coats of RC-Special were sprayed. A seal coat of SS-2B asphalt was sprayed on immediately afterwards.

In the fall of 1964, another seal coat was applied, consisting of an asphalt clay emulsion (C-13-E). This was the last work that was done on this catchment other than maintenance.

Plant growth, particularly yucca, was a continual problem on this site. The vegetation was removed several times. This catchment, however, has been abandoned because a new pipeline for stock water was constructed within one-quarter mile of the water trough.

Five Houses Catchment

This catchment was constructed in the fall of 1962 and spring of 1963 in a sandy area; 4- by 12-foot aluminum sheets were nailed onto a creosoted frame of 2 by 4's. The size of the completed area was 24 by 100 feet.

The slope on this area was approximately 6 percent. To get this much slope, it was necessary to bulldoze the area to obtain material for the base of the catchment. Due to the lack of suitable material and the amount of dirt that had to be moved, this site was about one-third the size that it should have been. The least amount of rain would cause water to run into the tank, but it never filled the bottom of the tank with more than a few inches of water. This catchment was maintenance free until 1969. It has since been abandoned.

Tovar Mesa Catchment

Again, this is one of the few catchments constructed using the natural topography of area without very much initial preparation. The site consisted of a sandstone slope with a natural depression and drainage at the lower end. In 1961, Hopi men cut and hauled stone blocks to the site. A concrete and rock dam was constructed at one end of the shallow rock bowl, forming an area that would store approximately 335,000 gal of water.

Eventually, this site proved unsuccessful, primarily due to the fact that the dam was not keyed into sandstone and the concrete failed to form a good bond with the sandstone. As a result, it leaked and failed to hold water.

HUALAPAI RESERVATION

Although, 14 catchments were constructed on the Hualapai Reservation. Twelve of these, constructed between 1957 and 1960, generally involved the same materials and construction principles and will be discussed as a single entity. The remaining two will be discussed individually.

Catchments 1 through 12

The first two catchments were constructed in 1957 on the "Big Burn" of 1953 in the northeast section of the reservation. These catchments were the first ones tried by the Bureau with the exception of the Shungopovi Catchment on Hopi. They were 60 by 90 feet in size and consisted of Gulfseal asphalt sheets, 3 feet by 12 feet by 1/2 inch. The sheets were butted together and lapped with gusset strips 5/32 inch thick by 9 inches wide cemented with hot asphalt cement. The edges of these gusset strips were pointed with a cold applied mastic so as to reduce any pocketing effect of moisture adhering to the joints.

In 1958, two more catchments were constructed using 1/4-inch by 4-foot by 12-foot Sealtite Hydromat asphalt liners. The size of these catchments was increased to 10,000 ft^2 (100 by 100 feet). They were constructed like the ones in 1957. Gusset strips, 1/4 inch by 8 inches were used over the joints cemented by hot asphalt cement and pointed with cold applied asphalt mastic.

Two more catchments, very similar to the 1958 catchments, were constructed in 1959. The first six catchments were installed by using local Indian labor under BIA supervision, except for storage tanks, which were contracted for fabrication at each site.

In 1960, six catchments were constructed under contract. They were constructed the same as the ones built in 1958 and 1959. The slopes on these catchments varied from 6 to over 10 percent. The one on the steep slope of over 10 percent proved to be less efficient in that the asphalt on the upper portion and along the upper sides pulled away from the berm, allowing water to "wash" under the pavement. More than the average amount of rippling occurred in the lower portion of the pavement.

All these catchments had problems with plant growth pushing through. In addition, the action of the heat and cold caused splits in the mats. Also, the gusset strips pulled loose, allowing plant growth to emerge along the seams. With one exception the catchments are all inoperative at present due to lack of maintenance. They should have had seal coats of asphalt applied periodically along with the removal of the plant growth. This would have retarded shrinkage and curling.

Catchment No. 4 had some patch work done about 1962. A section of it was patched with fiberglass and asphalt. This material has endured to date with no new plant life invading from below, although vegetation has come up immediately adjacent to it.

Nelson Road Catchment

This catchment has been developed with the assistance, direction, and cooperation of the U.S. Water Conservation Laboratory. It was originally constructed in 1962 with aluminum foil bonded to the ground with asphalt. This treatment proved unsuccessful in that high winds immediately blew the foil away. In the spring of 1963, two base coats of RC-Special were applied. This was covered immediately by a seal coat of SS-2B on one half of the catchment with the other half receiving no further treatment at the time. After 7 months, the sealed half was in good condition whereas the other half had failed (1).

In the fall of 1963, the unsealed half was treated by spraying an additional base coat of RC-Special. This plot was then treated by sealing half of it with SS-2 and the other half with SS-2B. Seven months later, the entire catchment had begun to crack with no differentiation noted between the various types of treatment (1).

In the early summer of 1964, the catchment was completely reconstructed by disking the old pavement, mixing it with 4 inches of soil, and rolling it. A base coat of MC-250 was applied followed by a seal coat of asphalt-clay emulsion (1). This catchment received no maintenance other than weed removal after this treatment. It was still shedding some water up to the summer of 1973, and there were seepage problems with the storage area, which made the situation ineffective.

The surface was removed from this site in the early fall of 1973. Fiberglass (2 oz), in 50-inch-wide rolls, was laid and sprayed over with CSS-1H asphalt as a base coat. This was followed up approximately 3 weeks later by applying an asphalt-clay emulsion (C-13-E) by hand mopping it on. There is still some work to be done on this site this spring in order to complete it.

The pit tank was initially constructed at the lower end of this catchment and several problems were encountered. The first of these was a steep rock outcropping on the south slope of the pit (the slope nearest the catchment), which made it much steeper than was originally intended. The second problem was that the outlet pipe from the storage pit to the watering trough could not be laid as deep as originally intended due to rock layers in the soil. Lack of time to do the job effectively left a high spot in the gravity flow line, making it impossible to completely drain and utilize all the stored water.

Due to the steepness of the south slope of the pit, the asphalt-fiberglass lining separated at the seam adjoining the catchment surface in spots and shrunk causing wrinkles on the side. In addition, the rock outcroppings rubbed holes in the material allowing for some water seepage. For unknown reasons we have never been able to explain, this pit tank never held water for any length of time since its initial installation.

We are attempting to correct the entire project. The tank will be reconstructed with the outlet pipe being lowered and the rock surface of the tank being tapered and smoothed to eliminate the puncturing problems. In addition, the tank will be relined and sealed with new material, probably asphalt and fiberglass.

Blue Mountain Catchment

Again, this was a project carried out in cooperation with the U.S. Water Conservation Laboratory, which furnished much of the technical assistance, materials, and equipment used in the construction. The original treatment was made in 1962, with asphalt fiberglass covered with aluminum foil. Although the site had been treated with a soil sterilant, a yucca plant started growing. Due to the toughness of the material, the yucca could not grow through the surface, but raised it up allowing the wind to destroy it.

In the spring of 1963, half of the catchment was treated by giving it a base coat of RC-Special with the other half being left untreated. A month later, a seal coat of SS-2B was put on the treated half. In the fall of 1963, the untreated half was sprayed with RC-Special only. No seal coat was applied. Neither of these treatments held up. The unsealed half disintegrated within 9 months, and the sealed section was cracked extensively (1).

In the fall of 1964, a base coat of MC-250 was sprayed on the entire catchment without disturbing the remains of the original surface. This was followed up immediately with a seal coat of SS-2 on the entire area. Half of the catchment was given an additional seal coat of an experimental aluminum spray (1).

The storage consisted of two round steel tanks, 25,000 gal each, connected together. A cover was made by making a circular framework with 1 1/2-inch plastic pipe, covered with 30-mil butyl rubber sheeting. Several inflated inner tubes were placed underneath to keep the cover afloat when the tank was filled. Due to a lack of moisture in the tanks, these covers deteriorated and were not effective. The only work done on this site has been intermittent clearing of vegetative growth. No additional seal coating has been performed, thus the site is not functioning efficiently.

KAIBAB-PAIUTE RESERVATION

Only one catchment, Semen Cistern, has been constructed on this reservation. It was constructed on a very sandy slope subjected to fairly high wind velocities causing considerable drifting of sand.

Originally, there was an 80,000-gal concrete cistern at this site, which was spring fed. It was built in the 1930's, and the spring that fed this system dried up leaving it useless for many years.

In the winter of 1959, the site above the cistern was cleared of brush and a catchment built about 18 inches above the ground. Prefabricated, concrete, wedge-shaped pillars were set in the sand to form a foundation. Salvaged creosote bridge timbers were bolted to the pillars.

Corrugated, asphalt-coated galvanized sheeting was overlapped and spiked to this framework. Across the lower end of the catchment, heavy, corrugated road culverts (18 inches in diameter), cut longitudinally and welded end to end, were installed to form a collection trough. This trough drained toward the center with an 8-inch pipe leading from it to the cistern.

For many years, the catchment was practically maintenance free with the exception of removing drift sand periodically. Now, however, one of the timbers has broken, allowing the roof to sag and separate the sheeting. This in turn has funneled water underneath the catchment, causing some erosion around the pillars allowing the catchment surface to sag. The fence around this area is down and the culvert collection trough is partially filled with blown sand. In spite of this, the cistern was full in October 1973.

This has probably been one of our best and most valuable catchments. However, it would have been the most costly if it had not been for the fact that most of the material was surplus or salvaged.

PAPAGO RESERVATION

Three catchments have been constructed on the Papago Reservation. One of these, the Pan Tak Catchment, was primarily designed to furnish domestic water for the village, rather than for livestock water.

Pan Tak Catchment

This catchment was constructed in 1966 with the financial assistance of Esso Research Company. It is the largest catchment we have built and covers approximately 2-1/4 acres. The material used was an Esso asphalt product. The initial treatment consisted of spraying the prepared site with water followed immediately by spraying it with asphalt. The theory behind this was that as the water penetrated the soil, it would help pull the asphalt down with it forming a more permanent bond.

The initial treatment was followed up in 1967 with another coat of Esso asphalt after weeds had emerged through the original surface. The Esso research people decided to respray it with asphalt on the theory that it would not only kill the top growth (perennial and annual) but also the roots. Needless to say, it did not achieve the desired results.

The water from the catchment drained into a 50,000-gal steel tank, which in turn would spill over and drain into a natural wash bed of fractionated and decomposed granite. The objective was to supply a ground recharge in the subsurface from which a well would be drilled to pump potable water.

As stated earlier, this catchment was designed to furnish domestic water for the village of Pan Tak with the agreement that the Indian Health Service would take over and provide for the well, pump, and water storage tank, and a community hydrant outlet. The project was never completed as planned; they drilled a well above the recharge area. However, the villagers are still using this site and open tank to supplement their well water.

There has been a considerable amount of annual and perennial vegetation growth on this catchment. Since the initial installation, no maintenance was provided other than the vegetation being cut off approximately 4 years ago.

After the second coat of asphalt was put on this site, the Esso Research Foundation lost interest in it and abandoned the project approximately a year later. This site still has excellent potential and should be rehabilitated for livestock water purposes and piped to a short distance from the village.

Alhambra Valley Catchment

This catchment was installed in late 1964 and early 1965 with the financial assistance of the Esso Research Foundation. The initial installation was the same as at Pan Tak, that is, spraying the site immediately with water followed by an immediate spraying of Esso asphalt. It was retreated in 1966 at the time the Pan Tak catchment was constructed with another spraying of Esso asphalt.

Even though this catchment deteriorated badly and was in poor condition, it has always caught water. Weed maintenance was a continuous problem with perennial ragweed being the principal species. It was persistent because of the prolific network of roots, which were not effectively destroyed by the application of polyborochlorate herbicide.

This catchment was redone in 1973 by the University of Arizona in conjunction with the BIA. Basically, it was covered with a polyethylene sheeting and a pea gravel covering on top. When this site was visited last September, weeds were still a problem, with some perennial ragweed showing through cracks of the polyethylene where it was exposed to the elements.

San Vicente Ranch Catchment

In the summer of 1965, a catchment of Dow Chemical polyvinyl chloride (synthetic rubber) was constructed on the San Vicente tribal herd ranch. This material was all prefabricated and laid in place, including a bag for water storage constructed of the same material.

There was a continual problem of maintenance as both harvester ants and various rodents developed a liking for this material in their diets and continually ate holes in it. As can readily be seen, there was a continual problem of patching the holes. Also, the summer temperatures vulcanized the sides of the polyvinyl chloride bag together before the summer rains filled it so that very little storage capacity was available. As a result, the bag was taken out and the pit treated with bentonite to provide some stock water.

This site was refinished in 1973 as was the Alhambra Valley Catchment. The gravel was more varied in size here than the previous one described. Also, the tank was relined with masonry cement on a chicken wire base. Last September it was necessary to patch the pit tank as surface cracks were showing up in it. This later work was also done in conjunction with the University of Arizona.

SAN CARLOS RESERVATION

Four catchments have been constructed on the San Carlos Reservation, including probably the most unique one, that of using a highway as our catchment area.

Highway 70 Catchment

This was constructed in 1958, using U.S. Highway 70 as the catchment area. One of the highway drainage drops was tapped to collect the rainwater, which was piped several hundred feet below and away from the right-of-way to a 20,000-gal tank that stays full about half of the time.

Other than occasional clogging of the drainage drop and pipeline, this site is practically maintenance free. Of course, the catchment site, the highway itself, is maintained by the State.

In spite of the discoloration of the water from the highway asphalt, there have been no detrimental effects to the livestock. This asphalt oxidation caused the stockmen to reluctantly accept the site as a benefit.

Mount Turnbull

This site was constructed in 1958 in an isolated, high, semidesert range with no water available. The material used was 1/4-inch Hydromat asphalt sheets similar to the ones described already. Practically no maintenance was performed, yet the catchment provided stockwater most of the grazing season. At first, the Indian stockmen were skeptical of it, because of the discoloration of the water from the asphalt.

In 1971, the remains of the curled and shrunken asphalt sheets were removed and, with assistance of the U.S. Water Conservation Laboratory, replaced with a fiberglass mat sprayed with a cationic asphalt emulsion.

Maverick (Seneca) Catchment

This catchment was built in 1966 and 1967 in the headwaters of the Seneca drainage with the cooperation of the U.S. Water Conservation Laboratory. Initially, the apron was prepared by burning the vegetation and then spraying it with a coat of silicone water repellant. Other than burning the vegetation, no other site preparation was done. The silicone coat temporarily waterproofed the surface, but the coat broke down and was not very efficient. The deep pit on this catchment was lined with 20-mil butyl rubber liner. Because the material was defective, the original liner had to be replaced.

This catchment site was retreated in 1969 by spraying it again with a silicone water repellant. Again, this material did not prove satisfactory and broke down.

In 1972, this area was treated by spraying with hot paraffin. At this time, the treatment is still being studied by the crew from the U.S. Water Conservation Laboratory. It appears to be very effective and low in cost.

Standing Rock Catchment

This catchment was built on the crest of a hilltop, which formed a very irregular and steep site. The catchment was constructed in 1965 with the cooperation of the Esso Research Foundation. The raw surface is primarily a natural decomposed granite, which was sprayed with an Esso asphalt product. A 50,000-gal tank was installed below the catchment site.

Although the site was initially treated with polyborchlorate, not all of the perennial vegetation was killed. Due to the porous granitic base, moisture traveled below the asphalt surface and caused soil upheaval spots on the catchment area. As a result, some of the perennial vegetation re-emerged.

This site was refurbished by respraying it with Esso asphalt. Other than removing the existing vegetation prior to respraying it, no other special site preparation was done. This application held up only a short time before the upheaval re-occurred. The only maintenance done has been cutting and removing the vegetation and applying asphalt as patches.

UINTAH AND OURAY RESERVATION

Sam's Canyon is the only catchment that has been built on the Uintah and Ouray Reservation. It was constructed in 1966. A 4-foot-deep excavation was dug, and then a framework of creosote-treated pine was constructed in the excavation. This framework consisted of 6- by 6- by 42-inch uprights on 4-foot centers and 4- by 4- by 48-inch cross-members. Once the framework was in place, the excavation was back-filled and compacted level with the top of the frame. The outside dimension of the frame was 60 by 90 feet.

Standard gage, 4- by 12-foot corrugated galvanized roofing was laid over the framework and fastened with 4-inch aluminum roofing nails. A 4-inch galvanized pipe was attached to the lower end of the collection trough and then to a 12,000-gal storage tank with a wire mesh trap installed at the outlet of the collection trough to keep debris from getting into the storage tank. The catchment area was fenced to keep livestock from damaging the apron.

Since the installation was completed, it has received only minor maintenance. Local residents are well satisfied with it and state that it continues to function beyond their original expectation.

NAVAJO RESERVATION

While this reservation is not within the Phoenix Area jurisdiction, the Navajo Agency and tribe have built approximately 15 catchments on the western Navajo. The first six were built in the Cedar Ridge-Bodaway country between U.S. Highway 89 and the Colorado River.

After the initial clearing and preparation of the site, they hauled sand and spread it to prevent plant stubs, rocks, etc. from puncturing the catchment material. The catchment itself is constructed of butyl rubber with a butyl rubber bag for storing water. After the initial installations, they are now installing "pop off" valves to release air pressure built up underneath the surface. This was found to be necessary after one of the first ones acted like a balloon and had to be punctured to relieve the pressure underneath it. Also, they have resorted to a heavier butyl rubber in subsequent construction.

The Navajo Agency seems to be satisfied with the performance of these catchments saying that they are relatively maintenance free other than having to occasionally patch tears in the rubber. According to reports, the biggest problem with them is that range users themselves occasionally attempt to destroy one with a knife or other sharp instrument because of feuds with neighboring stockmen.

SUMMARY

In most instances, our success with catchments on Indian lands in the Southwest has been limited. The reasons for these failures, as seen by the authors, are briefly discussed below.

One of the primary factors in the failure of catchment basins within the BIA has been the reluctance of some technicians to accept the practicability of the basins. As a result, they have been negligent in seeing that proper maintenance was performed.

Another big factor is that stockmen use these areas. With few exceptions, these ranges are being used in common by a few to several stockmen. These stockmen may be part of a large association or they may be running their livestock in common with no formal organization bonding them together. Maintenance on the catchments as well as other range improvements is often negligible unless actually done by the tribe. The individuals are usually looking for "George" or "Uncle" to do it rather than assuming the responsibility themselves. Where one individual or family group is using an area and has it under their exclusive control, the maintenance has generally been pretty fair. However, this has been the exception rather than the rule.

Many of the individuals using tribal lands for grazing expect the tribe to maintain the range improvements, and the tribe in turn expects the range users to perform this maintenance. As a result, there is a standoff with little or no maintenance being performed by anyone. In many cases, the Indian stockmen are paying little if any grazing fees, and funds collected are not sufficient for the tribes to perform the maintenance. On reservations where the tribes are collecting some grazing fees to maintain the range improvements, tribal subsidization is often necessary. An example of this is the Hualapai where the tribe is using the meager grazing fees to maintain their pipelines and wells. At present, annual maintenance costs approximately $18,000, with annual grazing fee income being about $12,000. With many tribes, the Council is reluctant to raise the fees high enough to cover this. Unfortunately, many of the Council members are also livestock operators and use political strength to subsidize themselves.

Another cause for catchment failures is the lack of understanding by the operators as to what is needed in the way of maintenance, and when this maintenance should be performed. Unfortunately, most of us have been looking for some cheap, economical means of securing water for our livestock without maintenance.

The U.S. Water Conservation Laboratory is in the process of publishing a handbook for ranchers to use in the selection of sites, materials, determination of size of catchments and storage, and last, but not least, a maintenance program.

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WATER HARVESTING CATCHMENTS IN THE SAFFORD DISTRICT, SOUTHEASTERN ARIZONA

Mark W. McBride and Larry W. Shiflet [1]

NEED FOR WATER

Water is scarce in southeastern Arizona, as in other arid regions. Domestic water is obtained from wells and springs. Water for livestock and wildlife is provided from springs, streams, wells, and from runoff collected in reservoirs and catchments. Agricultural water comes from surface runoff, rivers, and wells. Industrial water is generally limited to wells, streams, and springs.

As we consider the need for water, let us ask ourselves this question, "Can we afford not to develop means and methods of water production, collection, and storage?"

The demands for water are constantly increasing, with growing demands for agricultural commodities. With the encroachment of subdivisions, industrial development, and recreation demands, our sources and supplies of water are rapidly diminishing.

It is possible to foresee improved techniques of cloud seeding in which this vast resource will be more effectively tapped. As this happens, let us be prepared to harvest, store, and use this water as needed. Someone once said, "Water we don't have, we can't use."

The water needs on Bureau of Land Management (BLM) lands are determined during planning, as part of the planning system in which all uses and requirements are considered. These water needs are determined through field examinations, surveys, and evaluations by BLM specialists assisted by the recommendation of interested and concerned parties. During this planning period, public meetings are held and interested people, organizations, and other groups are invited to present their ideas, suggestions, and objections to BLM proposals. This permits input into the plan from additional sources. An environmental analysis is also required to cover all the proposed work, development, and management that is to be involved.

BACKGROUND

The Safford District is located in southeastern Arizona, north from the Mexican border to the Apache Indian Reservation, and includes 1,500,000 acres of national resource lands, formerly called public lands.

Elevations range from 2,500 feet on the Gila River to 8,300 feet on the Dos Cabezas Mountain. Mount Graham, which is adjacent to Safford District, and located in the Coronado National Forest, rises to about 11,000 feet.

The topography consists of wide valleys, rolling hills, and steep desert mountains. Drainage is into the Gila River or a tributary.

Soils are generally alkaline, clay and sandy loams of volcanic and limestone origin, and will vary from shallow and rocky, to deep rock-free valley loams. Most of these soils are highly erodible and classified as "frail lands."

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Precipitation ranges from 6 to 8 inches in the valleys to 12 to 16 inches above 7,000 feet, and comes generally during the summer months. Isolated torrential storms of 2 to 3 inches in less than an hour occur at different times and locations throughout the summer, causing heavy damage to watershed, crops, municipal developments, and highways.

Temperature readings of 110° F in the summer, and 25° in the winter are not uncommon.

Vegetation generally consists of trees, shrubs, half-shrubs, and forbs such as mesquite (Prosopis sp.), saltcedar (Tamarix), juniper (Juniperus sp.), pinyon pine (Pinus cembroides), sycamore (Platanus wrightii), turbinella oak (Quercus turbinella), willow (Salix sp.), agave (Agave sp.), cactus (Opuntia sp.), yucca (Yucca sp.), creosote bush (Larrea tridentata), snakeweed (Gutierrezia sarothrae), burroweed (Aplopappus tenuisectus), and saltbush (Atriplex sp.).

Grass is interspersed with the shrubs, trees, and bare soil. Some of the grasses include: tobosa (Hilaria mutica), alkali sacaton (Sporobolus arioides), gramas (Bouteloua sp.), threeawn (Aristida arizonica), bush muhly (Muhlenbergia porteri), lovegrass (Eragrostis sp.), sand dropseed (Sporobolus sp.), Arizona cottontop (Trichachne californica), plains bristlegrass (Setaria macrostachya), vine mesquite (Panicum obtusum), and other grasses not mentioned. Annuals are numerous and grow when there is adequate precipitation.

INSTALLATION AND USE OF WATER CATCHMENTS WITH STORAGE OF 25,000 GALLONS OR MORE

Use of the larger type catchment began in the Safford District in 1966. Since that time, several types and combinations of water harvesting areas, aprons, and storages have been used. Some have been satisfactory, and some have been less than satisfactory. The aprons and storages have been 10,000 square feet and 25,000 gal, or more, respectively. All BLM and cooperatively installed catchments are fenced. It is necessary to fence all apron areas and storage bags with netting wire to prevent damage from javilinas (a type of wild pig).

The catchments that have been installed consist of the following combinations:

1. Butyl rubber, nonreinforced, 1/32-inch (0.03125) apron and one-piece nylon reinforced butyl rubber storage bag.

2. Butyl rubber apron (as in 1 above) and an open-top steel tank connected with a 6-inch aluminum pipe.

3. Fiberglas-asphalt apron (1 oz material sprayed with 1/2 gal of cationic asphalt emulsion and mopped with 1/2 gal of clay asphalt emulsion per square yard) with one- or two-piece, nylon reinforced, butyl rubber storage bag.

4. Fiberglas-asphalt apron (as in 3 above) and connecting Fiberglas-asphalt storage tank.

5. Wet weather spring below a rocky hillside, with a small rock masonry dam and 6-inch aluminum pipe to carry water into a one-piece, nylon reinforced butyl rubber storage bag.

6. Slickrock cliff area of approximately 5 acres, and a 5-foot rock masonry dam with 6-inch aluminum pipe to carry water into a two-piece, nylon reinforced storage bag.

7. Plastic sheeting, gravel covered apron, and connecting tank of multilayered plastic sheet lining, and also lined with old rubber automobile tires, and tank filled with 2- to 4-inch rock.

SMALL WATER HARVESTING CATCHMENTS WITH 5,000 GALLONS OR LESS STORAGE

Several small water catchments of 5,000 gal or less, used to supply water for wildlife, were installed in the 1940's in cooperation with the State Game Department. They consist of:

1. Small, fan-shaped concrete apron 20 feet long, the top 30 feet and the bottom 5 feet in width. The water is diverted in a concrete chute and into 200- to 250-gal concrete covered tank. An open ramp leads into a restricted watering area.

2. Double-apron type of steel sheeting on wooden frames, each area is 400 ft^2 and slopes to center with drainage into a 5,000-gal steel ring tank with plastic liner. The tank was located beneath the apron area. These installations also have a ramp leading into a small wildlife watering device.

WATER HARVESTER CATCHMENT SITE SELECTION

General Area

In the selection of a general area in which to select a water catchment site, several things should be considered:

Is the area accessible to vehicles and installation equipment? Will additional access (road) be required? What is the soil depth and rock content? How much vegetation is there to be moved? How much handwork will be required? What is the precipitation and when does it fall? Is there a slickrock hillside in the vicinity? What environmental considerations and mitigating factors are involved?

Tentative Site

When a tentative site has been selected, determine the following:

How is the water to be harvested? What are the storage requirements? How is the water to be directed into the storage? Is access realistic? Is this a workable installation? What will the maintenance requirements be?

LOCATION OF APRON AND STORAGE ON A SELECTED SITE

The apron site may have a slope from 2 to 10 percent and should be of adequate size to collect the desired amount of water. The soil should be at least 4 inches in depth and with a minimum of rock.

A desirable site location is often on a smooth ridge or a saddle where there is a distinct break or drop in elevation a short distance from the apron site. If a saddle is used and has slope to each side, a water storage facility can be installed on each side of the saddle.

It is desirable to select the tank or bag location so there will be adequate fall from the apron, and so the pit can be dug and the outlet pipe installed before work begins on the apron site preparation. This will allow for required change that might affect the apron location, size, or shape. The high water level of the storage must be below the outlet from the catchment apron.

LOCATION OF ROCK SLOPE SITE FOR WATER HARVESTER AND STORAGE

This type site should be a half acre or larger with indications of water runoff. The slope is not critical, but should be 2 percent or more, with drainage into areas that will require a minimum of rock masonry diversions construction to collect and divert water to the storage facility. The tank site should be located near the collection area to reduce the pipe requirement.

CONSTRUCTION AND CONTRACT SPECIFICATIONS

Contracting

There are various methods of constructing catchments, but the BLM is bound by the Federal Procurement Regulations, which require that these construction, installation, and maintenance contracts be let through competitive bids and with the contract being awarded to the lowest responsive bidder.

Specifications

Contract specifications must be feasible for the specific job and site; they must be concise, realistic, and workable, if bidders are to submit bids that will be compatible with the engineer's estimate.

Our specifications are constantly upgraded and improved to include new ideas, materials, or methods.

The use of different types of catchment specifications depends upon whether or not the catchment can be contracted, and at a comparable price of installations with other specifications. The availability, cost, and ease at which materials can be used are also factors in the selection of the type of catchment to be constructed.

DISCUSSION OF WATER HARVESTING CATCHMENTS AND STORAGE

Problems Encountered

During the installation or maintenance of the various catchments that have been discussed, numerous problems have been encountered; some have been worked out and other remain to be solved.

Butyl rubber aprons are easily installed; replacement may be required in 5 to 6 years. Whenever a break in the rubber occurs from deer, rodents, coyotes, or any other source, a condition has developed permitting wind to get beneath the apron and tearing develops. Often, the rubber apron balloons, tears in several places, and part may be blown off the site. During periodic maintenance, smooth rocks of 5 to 10 pounds have been placed in rows across the apron to reduce tearing, but this has had only a minor effect.

The Fiberglas-asphalt aprons require resealing with clay asphalt emulsion every 3 to 5 years. The surface is often broken from below by plant growth that was not killed by the soil sterilant, by burrowing rodents, and by ants, and from above by animals, wind, and vandals. These surface breakages are easily repaired with Fiberglas and clay asphalt emulsion.

The Fiberglas-asphalt apron is the most durable and maintenance is easily accomplished. Chopped Fiberglas mat, rapid setting cationic liquid asphalt emulsion, and roofing-type clay asphalt emulsion form a firm, durable apron that adheres closely to the soil.

To prevent apron slippage on slopes from 5 to 10 percent, it is recommended that fortypenny nails with a 2-inch sheet iron washer be driven through the apron and into the ground, at 2-foot intervals and in rows every 5 feet across the upper half of the apron. This procedure is now included in contract specifications.

The plastic sheet, gravel covered apron requires only a slight slope and is not recommended on steep slopes. The large sheets of polyethylene plastic are cemented together and used in the same manner as the other aprons. The plastic is covered with a shallow layer of fine gravel.

Damage occurs from plant growth, rodents, and ants from below; and from animals, wind, and vandals from above. Maintenance consists of removing the source of damage, filling the hole, patching with plastic tape, and covering with new gravel.

Storage

Several types of tanks have been used including nylon reinforced butyl rubber (both one and two-piece), steel open top and concrete botton, and Fiberglas-asphalt tank with pipe, wire, and Fiberglas-asphalt top.

Butyl rubber bags with the inlet or overflow pipes installed in the top side have given trouble. The rising and falling of the water level tends to kink the rubber tubing, thus cutting off the inflow and overflow. On either the one- or the two-piece bag, this can be corrected by relocating these pipes into the bottom half of the bag. Cement a new boot at each location and allow for any slippage of the one-piece bag in the pit. The water level in the bag can be adjusted by raising or lowering the overflow pipe level over the berm.

Other problems developed with the one-piece bag when installed in a hillside pit with a high berm or fill at the lower side. When the bag fills, it tends to roll toward the lower side, the grommets in the upper corners and along the sides tear out, allowing the bag to slump into the pit. By building the lower berm higher than the upper edge of the pit, the forward roll of the bag will be reduced.

Where plastic pipe is used in the outlet pipe, it often kinks and frequently breaks if the bag rolls. When this happens, the pipe must be dug out and replaced. It is recommended that steel pipe with a smooth end to clamp into the bag, be used as replacement.

Fiberglas-asphalt storage tanks have been constructed with two layers of Fiberglas in the pit and a fabricated top. Presently, a means of controlling seepage is required before additional tanks of this type will be constructed.

Steel tanks with concrete bottoms have been satisfactory; however, it is recommended that when constructed, the inside be mopped with the rapid drying cationic asphalt emulsion to prevent seepage.

The rock-filled tanks have not presented any problems nor have they required maintenance. If a leak or broken pipe developed, it would be very difficult to make proper repairs. When this type tank can be constructed by contract at the approximate cost of the other type tanks, we will consider them in our water development program.

Recommendations

When selecting water development locations, consider rock slopes, slickrock areas, and ledges for water harvesting sites. An area of greater size can be included in the rock slope type apron. Water can generally be diverted to wherever necessary with small rubble rock masonry diversions, which are inexpensive, easy to construct, and effective in diverting water into collection areas. This water may be carrying silt, and it is recommended that sediment traps be installed above the water collection boxes. Select a site for the storage facility that can be enlarged if necessary. A large storage facility, installed below a large water harvesting area, should be capable of storing a 2-year supply of water and provide carryover water for dry seasons. Available water is necessary if rotational grazing systems are to be used and their benefits realized.

The cost of this type of installation is much less than the cost of the other type of catchment installations. The collection area can be much larger and water yield will be greater and the maintenance costs less.

Fencing should enclose the silt basin, pipe, and storage facility on this type of installation.

Table 1 shows the available cost figures, type of installation and storage that was constructed, and the year of construction through fiscal year 1973.

TABLE 1.--Cost of catchment materials, installations, and fencing

Year installed	Name of catchment	Costs			Types of areas	Types of storages
		Material	Labor	Total		
1966	Dos Cabezas	$6,970	$1,644	$8,614	Butyl rubber apron 10,000 ft^2	Butyl rubber tank, 1-piece, 25,000 gal. 2 ea.
1967	Guthrie	4,151	1,800	5,951	----- do -----	Steel open top tank, 50,000 gal.
1968	Jones	3,953	1,100	5,053	----- do -----	Butyl rubber, 1-piece bag, 25,000 gal.
1968	Red Spring	2,168	520	2,688	Wet weather spring below rock hillside. Rock diversion 250', 6" aluminum pipe	Do.
1970	Whitlock	3,863	1,848	5,710	Fiberglas-asphalt apron, 10,000 ft^2	Do.
1971	Basin	3,450	1,500	4,950	----- do -----	Do.
1971-72	Mesa	5,177	2,044	7,221	----- do -----	1 ea. 1-piece, 1 ea. 2-piece, 25,000-gal bags.
1973	El Toro	2,902	2,115	5,017	----- do -----	1 ea. butyl rubber 2-piece 25,000-gal bag.
1973	White Mesa	2,505	2,035	4,540	----- do -----	Do.
1973	Mile High	2,515	2,075	4,590	----- do -----	Do.
1973	Talley	1,440	825	2,265	5-acre slickrock hillside. Rock masonry dam 200', aluminum 6" pipe.	Do.
1973	Red Hills	2,916	3,375	6,291	Fiberglas-asphalt apron 10,000 ft^2	Fiberglas-asphalt tank, 40,000 gal.
1973	Barton Wash	2,807	3,455	6,262	----- do ------	Do.

Table 2 shows the water production from various precipitation rates and from specific size areas. The gallons of water produced from the 5-acre slickrock site in a 12-month period are as follows:

8-inch rainfall area:

217,800 ft^2 at 5.01 gal/ft^2=1,091,179 gal

12-inch rainfall area:

217,800 ft^2 at 7.48 gal/ft^2=1,629,144 gal

TABLE 2.--Size of ground cover required to fill water storage bag in a 12-month period

Bag size (gallons)	Ground cover area (square feet)	Dimensions (feet)
	8-INCH RAINFALL AREA	
1,600	328	18 x 18
3,000	734	27 x 27
15,000	3,068	55 x 55
25,000	5,114	72 x 72
35,000	7,157	85 x 85
50,000	10,227	101 x 101
	12-INCH RAINFALL AREA	
1,600	214	15 x 15
3,000	401	20 x 20
15,000	2,005	45 x 45
25,000	3,342	58 x 58
35,000	4,679	68 x 68
50,000	6,684	82 x 82
	18-INCH RAINFALL AREA	
1,600	143	12 x 12
3,000	267	16 x 16
15,000	1,337	37 x 37
25,000	2,228	47 x 47
35,000	3,119	56 x 56
50,000	4,456	67 x 67
	24-INCH RAINFALL AREA	
1,600	107	10 x 10
3,000	200	14 x 14
15,000	1,003	32 x 32
25,000	1,671	41 x 41
35,000	2,340	48 x 48
50,000	3,342	58 x 58

DESIGN AND CONSTRUCTION OF ROADED CATCHMENTS

J. L. Frith [1]/

INTRODUCTION

Roaded catchments are a cheap method of catchment improvement used to enhance runoff to stock water storages (dams) in the wheatbelt of Western Australia. Other papers in this symposium describe the region in which they are used (1) and theoretical aspects of design (5). This paper presents details of current practice in layout and construction.

Roaded catchments, as their name implies, are areas of formed, compacted, parallel ridges of earth made in a similar fashion to earth roads. The road surface is cambered steeply and is made as smooth and impervious as possible. Drains between the roads are surveyed on grades that permit water to reach the dam expeditiously but with a minimum of erosion.

DESIGN OF ROADED CATCHMENTS

Sites

Sites should (1) be above the dam; (2) be not more than 400 meters from it; (3) contain clay soil or a clay subsoil within not more than 1 m of the surface (Loose sands and gravels, loams, and friable self-mulching clays are unsuitable materials for surfacing catchments.); and (4) have a surface slope that allows the catchment drains to be alined on correct grades.

Layout

Individual roads vary from 5 to 12 m wide (crest to crest) and from 50 to 300 m long. Since the area of catchment can vary up to about 10 hectares, frequently more than one road, sometimes many are required.

Where ground slope is little more than the grade of road drains, roads can discharge directly in front of the dam. If numerous, they can be provided with a collecting drain.

On slopes of more than about 3 percent, collecting drains of the required grade would meet road drains at an angle too acute to be conveniently constructed. On steeper slopes, therefore, roads are usually discharged on a grassed waterway leading to the dam.

Beyond this it is not possible to generalize the pattern of layout. It will be influenced by considerations of ground conformation, depth and availability of clay subsoil, distance and height difference between the dam and catchment, and thickness of clay cover desired.

To prevent ponding of water at the outlet or extension of stored water in the dam over the catchment surface, road drains should not be cut below the full level of the dam. The slope of the ground surface and the depth of road drains thus specify a minimum desirable distance between catchment and dam.

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[1]/ District Soil Conservation Adviser, Soil Conservation Service, Department of Agriculture, Moora, Western Australia.

From a consideration of roaded catchment cross section (fig. 1), Frith and Nulsen (3) related depth of road drains to depth of topsoil and thickness of clay required to cover graded topsoil.

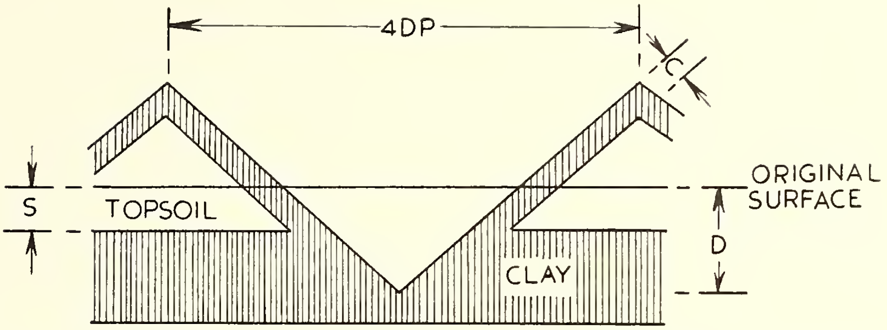

FIGURE 1.--Diagram of a roaded catchment cross section. D = depth of road drain below original ground surface, C = thickness of clay cover, S = depth of topsoil, P = reciprocal of the side slope of road surface, 4DP = width of road. After Frith and Nulsen (3).

This is given approximately by

$$2C = \frac{D^2 - 2DS + S^2}{D + S} \qquad (1)$$

where C = thickness of clay cover

D = depth of road drains below original ground level

S = depth of topsoil

D is found by substituting values of C and S. The relation is graphed (fig. 2).

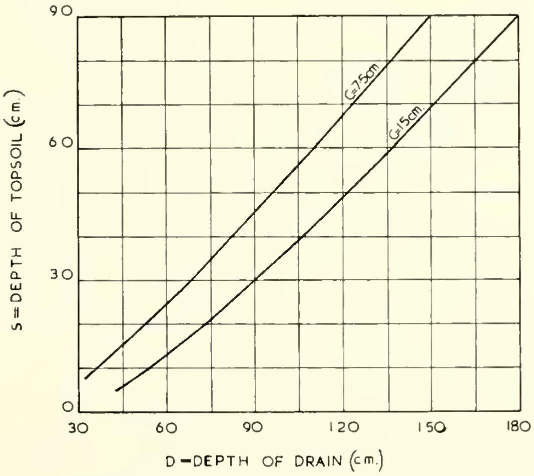

FIGURE 2.--Relationship between depth of topsoil (S) and depth of road drain (D) for cover thickness (C) of 7.5 and 15 cm. After Frith and Nulsen (3).

Clay Cover and Road Width

The depth to clay subsoil and the selection of a combination of road width and side slope, which will expose adequate amounts of clay to cover the catchment, are paramount factors. The construction of narrow roads and failure to achieve adequate clay cover were responsible for poor performance by many older Public Works Department catchments in Western Australia. This in turn led to serious underestimation of roaded catchment potential and the neglect of this means of providing much needed emergency public water supplies. Frith and Nulsen (3) suggested that an effective cover thickness of 3 inches (7.5 centimeters) might be required where a powered grader was used for construction. It has since been found that mixing of topsoil and subsoil clay during construction is increased when larger depths of topsoil are present. Current practice is therefore to design for an effective 15-cm thickness of cover where depth of topsoil exceeds about 20 cm.

If depth of road (D) is found from equation 1, width of road is given by 4 D P, where P is the reciprocal of the slope. The relation between width of road and depth of topsoil is graphed for three values of P and two values of C (figs. 3 and 4).

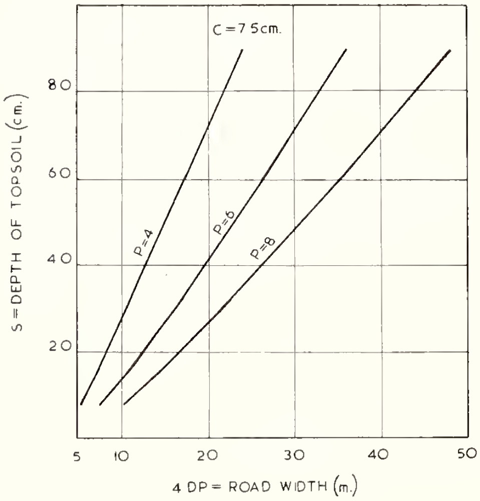

FIGURE 3.--Relationship between road with (4DP) and depth of topsoil (S) for road side slopes of 1/4, 1/6, and 1/8 and clay cover thickness of C = 7.5 cm. After Frith and Nulsen (3).

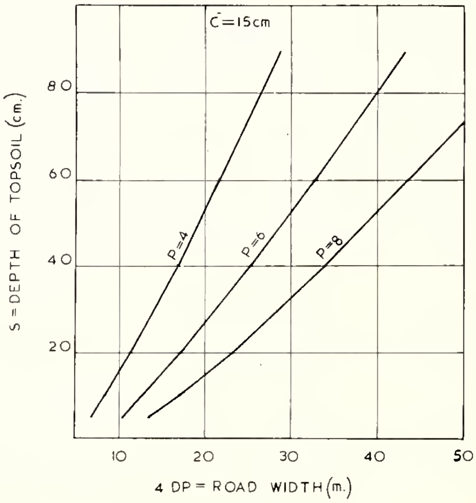

FIGURE 4.--Relationship between road width (4DP) and depth of topsoil (S) for road side slopes of 1/4, 1/6, and 1/8 and clay cover thickness of C = 15 cm. After Frith and Nulsen (3).

Slopes of Catchment Surface

The slope of the catchment surface, from road crest to outlet, is progressively decreased so that it is a maximum where flow is shallow and a minimum where it is deepest.

Road Side Slopes

Road side slope is made as steep as possible. It can approach 25 percent, but limitations of rollers used for compaction often reduce it to 20 percent or less.

The effect of side slope on catchment threshold has been discussed by Hollick. 2/ Threshold is that part of a fall of rain that does not reach the dam.

Side slope exerts a greater effect as the roughness of the finished surface increases. that is, increasing side slope decreases depression storage. If a steel roller is used and a smooth hard surface results, side slopes of 10 percent are probably quite satisfactory. Multitired rollers, although providing better compaction, tend to leave slight ridges, which collect and channel water prematurely. Resultant overflow of these small channels erodes the road surface at intervals. This problem is minimized by steep side slopes.

Increasing side slope also allows a decrease in the minimum width of road necessary to achieve clay cover. Since cost is related directly to road width, steep side slopes, within the capabilities of the machinery, make for low cost.

Steep, clay covered, compacted side slopes collect few if any seeds. Catchments so constructed over the last 4 years support plant growth only on the exposed triangular sections of overburden where a collecting drain cuts the roads.

Grades of Drains

In current Western Australia Department of Agriculture practice, the maximum permissible grade at any point of a road drain is related inversely to the length of contributing road about it, according to the following schedule:

Section of drain from end opposite outlet (in meters)	Percent maximum allowable grade
0 - 15	20
15 - 60	2
at 100	1
at 200	.5

The above are maxima. Road drains accurately constructed with slopes no more than 0.5 percent over their entire length are not noticeably less efficient than steeper drains.

Hollick (4) suggests that maximum drain grade at any point should be related to area rather than to length of road, especially since relatively wide roads are now employed.

This is a desirable refinement for which, however, no standards are yet available.

It is difficult to construct drains of roads on grades less than 0.5 percent without incurring some ponding of runoff. Lower grades in road drains are therefore avoided. Roads longer than 300 m could erode at this grade; 300 m is therefore a practical limit to road length.

Collecting drains, which may have to carry large volumes of water, must be given grades less than 0.5 percent. If some ponding results, this must be tolerated if excessive erosion is to be avoided.

2/ Hollick, M. The development of improved catchments for farm dams. Dept. Civ. Engin., Univ. West. Austral. 1971. (Unpublished.)

CONSTRUCTION

Compaction

Because roaded catchments in Western Australia are built mostly in remote rural areas, watering equipment is not usually available. The period during which catchments can be constructed is restricted to autumn and spring when soil moisture is about the optimum for compaction. In summer, dry clay subsoils are difficult to scarify and impossible to compact. In winter, wet conditions limit the operation of wheeled machinery. In the northern wheatbelt, where the spring season is short, fallowing intended catchment sites can prolong the construction period.

Compaction and smoothing produced by rolling during construction are important factors in performance and durability. Observation of some unrolled catchments suggests the omission of rolling will raise catchment threshold by about 5 mm. A study of dam volume - catchment area relationships further suggests that this increase will double the area of catchment required to provide a given amount of water.

A further observation is that smoothed, compacted catchment surfaces do not provide a germination medium for plant seeds; whereas rough, unrolled surfaces often do. Since roller rental forms a small part of total machinery costs, its inclusion is firmly advocated.

Sequence of Construction

1. Areas above the dam are inspected with a soil auger for underlying subsoil clay. If this clay is found and the ground conformation is satisfactory, about 20 holes per hectare are bored to ascertain the depth of topsoil.

2. Depth of road drains and width of roads are read from graphs (figs. 2, 3, 4). The lower limit of the outlet of the catchment is fixed in relation to the full level of the dam.

3. A trial layout is decided. The drain of the first road is surveyed and pegged. The next road is pegged a road width from it. If the grade is within the limits prescribed above, the process is repeated until the planned area of catchment has been pegged.

If the grade is outside the limits, a new alinement at correct grade is surveyed several road widths apart from the last road. Intervening roads are then made parallel to this survey. Layout is adjusted to avoid the resultant islands of unroaded grassed ground as much as possible.

4. A heavy power grader is used to remove topsoil from the center of the drains to well beyond halfway to the crests. The overburden is compacted by roller.

5. Exposed subsoil clay is graded from the drains and spread in successive thin layers on the side slopes. Each layer is rolled. Grading is continued until the designed depth of drain has been reached.

Grader hours worked per hectare of catchment are related directly to the depth of topsoil. An average operator could produce the following outputs:

Depth of topsoil (centimeters)	Hours per hectare
15	10
30	15
45	20

Variations in size and power of machine, operator skill, soil coherence, moisture conditions, and even the weather combine to produce a fourfold variation in output per hour. Unfortunately, the greatest and least predictable factor seems to be operator skill.

Tractor-drawn rollers are required for about 4 h/ha regardless of depth of topsoil.

6. Where roads are to discharge onto grass, attention is given to maintaining continuous fall in the drain where it intersects ground surface at the outlet.

7. If a collecting drain is used, it is pegged before construction commences. Roads are cut through the drain to full depth. The collecting drain is then resurveyed to connect the floors of the finished road drains with a suitable grade (less than 0.5 percent). It is important that the floors of collecting drain and road drains coincide precisely. If the collecting drain is too low, the road drains will erode. If it is too high, ponding raises the threshold. If possible, the inside downhill face of the collecting drain is covered with clay to provide additional shedding surface.

8. The catchment is fenced to exclude stock.

Maintenance

Past recommendations on roaded catchment construction (2, 6, 7) have stressed the need for maintenance to remove plant growth. This was necessary because, on earlier catchments, adequate side slope and clay cover frequently were not obtained. Catchments made according to methods described above have been in existence now for 4 years. To date, they show little, if any, evidence of supporting plant growth. The exact length of weed spraying intervals is unknown, but it is probably greater than 5 years.

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DISCUSSION

SESSION II, Part 2--Sol Resnick, Chairman

G. FRASIER: What is the catchment efficiency of the roaded catchments?

R. NULSEN (for J. Frith): Presently we have very few measurements on catchment performance. Rough observations indicate that most well-constructed, well-compacted, clay-covered catchments will run water after 4 to 5 mm of rainfall.

D. FINK: What are the characteristics of the clays used in roaded catchments?

R. NULSEN (for J. Frith): We try to avoid any calcareous or self-mulching clays. Most other clay types with even low degrees of cohesiveness can be used.

SESSION III, Part 1--Charles Staff, Chairman

HYDROLOGIC ASPECTS OF WATER HARVESTING IN THE NORTHERN GREAT PLAINS [1]

Clayton L. Hanson, Earl L. Neff, and David A. Woolhiser [2]

Ponds are an important source of water for livestock in many parts of the United States. In South Dakota, about 3,500 ponds were constructed annually during the last several years. [3] The design of such ponds is usually minimal because of the low cost of each structure. However, as water becomes more valuable, it is worthwhile to develop a sound theory of pond design, which can serve as a basis for developing regional information necessary for improved design of specific storage structures.

A computer procedure was developed for simulating storage of water in ponds based on hydrologic information, contributing area, number of cattle, length of grazing season, seepage estimates, and evaporation rates. This program, along with data on construction costs, value of water for alternative uses, and alternative livestock watering methods, could be used to determine the most economical type and size of stock pond for use at a given location.

SYSTEMS APPROACH TO POND DESIGN

The systems approach has three essential steps: (1) system description, (2) selection of an objective function, and (3) optimization. In system description, a mathematical (or, in some cases, a material) model is constructed, which describes the important aspects of the system, and then the design criterion is decided. This criterion is described by the objective function, a single-valued function of the design variables of the problem. The mathematical notation is

$$F = f(a_1, a_2, \dots, a_n) \tag{1}$$

where F is the objective function and the a_i are design variables. Finally, the optimization step finds the set of design variables, a_i, $i = 1,2, \dots ,n$, that maximize or minimize the objective function. Each step is important. If the mathematical model does not describe the actual system, the other steps are not worthwhile; a poorly formulated objective function can lead to nonsensical results; and without optimization procedure, the first two steps cannot be fully utilized. However, this paper is primarily concerned with the system description.

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[1] Contribution from Agricultural Research Service (ARS), U.S. Department of Agriculture (USDA), Bureau of Land Management, U.S. Department of Interior (USDI), and Idaho Agricultural Experiment Station cooperating.

[2] Agricultural engineer, Northwest Watershed Research Center, Boise, Idaho; hydraulic engineer, Northern Plains Soil and Water Research Center, Sidney, Mont.; and hydraulic engineer, Fort Collins, Colo., respectively; ARS, USDA.

[3] Personal communication with David Tokash, USDA-SCS, Huron, S. Dak.

System Description

Assuming the observations of pond storage are continuous over a period of 1 year, a graph of storage versus time might resemble figure 1.

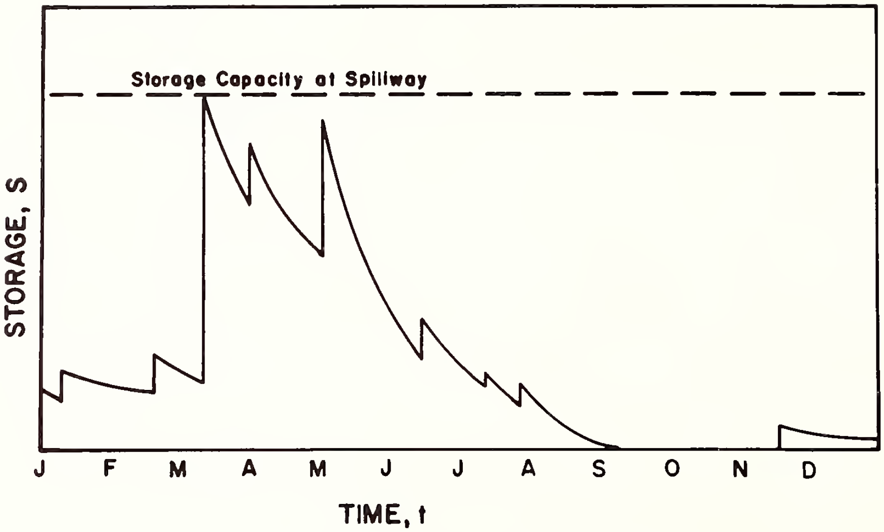

FIGURE 1.--Pond storage versus time.

In this example, the pond was filled by runoff once in March and was dry in September, October, and part of November. This graph is a sample function because it is only one sample of an infinite number of realizations of this process that could occur. If the rancher intends to graze the area served by this pond during the dry period, he must either provide another source of water or forfeit these grazing resources and move his livestock to another pasture. Either alternative is costly.

To develop a more formal description of the pond storage process, let us consider the diagram shown in figure 2. The symbols X_i, i = 1, 2, and Y_j, j = 1, ... ,4, represent the pond inflow and outflow.[1] $X_1(t)$ is

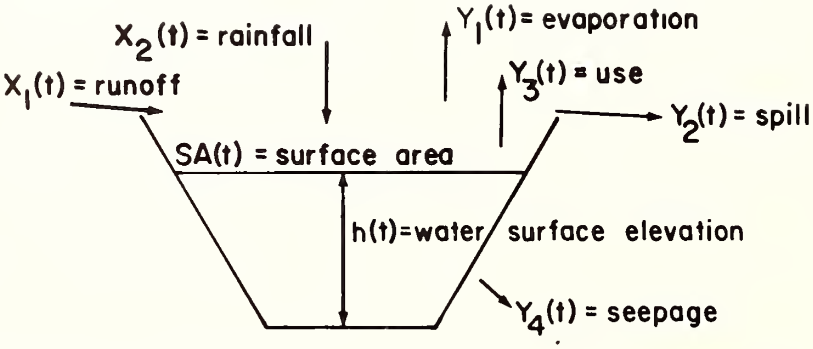

FIGURE 2.--Diagrammatic representation of a stock pond.

the surface inflow to the pond from a watershed of area (A), and $X_2(t)$ is the rainfall input to the pond. Outputs include evaporation from the pond surface, $Y_1(t)$; spillway outflow, $Y_2(t)$; the amount of water needed by the livestock, $Y_3(t)$; and the amount of water that seeps into the ground, $Y_4(t)$. The state variable is the amount of water in storage at any moment, S(t). and m is the maximum capacity of the pond. These inputs and outputs can be combined into a continuity equation.

$$X_1 + X_2 = Y_1 + Y_2 + Y_3 + Y_4 + ds/dt \qquad (2)$$

All variables in equation 2 are instantaneous flow rates. In practical situtations, we will consider the amount of input or output in some finite time period, such as a day, week, or month. The notation used in the discrete case is $X_i(k)$, $Y_j(k)$, $S(k)$, $k = 1, \ldots ,n$, where n is the number of periods in a year.

Since the inflows occur according to certain laws of chance, all the outflows and the amount in storage at any time are also probabilistic.

Because the pond inflow and outflow are complex in structure and because inflow processes are stochastic (random), simulation is the most effective technique for pond design. A daily time increment was chosen to effectively utilize existing data.

Stochastic Rainfall Model

Daily rainfall can be simulated, using a stochastic model, such as the Markov Chain-Exponential model, in which rainfall occurrence is described by a two-state Markov Chain with parameters q_o and q_1 (1, 3, 4, 7).

If no precipitation occurred the previous day, q_o is the probability of precipitation; and if precipitation did occur the previous day, q_1 is the probability of precipitation. The distribution function of daily rainfall is assumed to be exponential

$$F_{X_1}(x) = P\left\{X_1 \leq x\right\} = 1-e^{-\lambda x} \qquad (3)$$

where the parameter λ is the inverse of the sample mean of all daily precipitation, 0.01 inch or greater, on days with precipitations. The Markov Chain parameters, q_o and q_1, can be obtained for the 11 contiguous Western States and Texas for 7-day periods (5).

The simulation procedure consisted of generating a random number between 0 and 1 from a uniform distribution to determine whether precipitation occurred on any given day. If it did occur, another random number was generated and transformed to compute the amount of precipitation according to equation 3.

Runoff Models

The following exponential distribution function was used to simulate snowmelt runoff occurring during November through April. It was also one of the two functions used to simulate daily summer runoff, if rainfall occurred during May through October. The function is

$$F_{X_1(k)}(x) = P\left\{X_1(k) \leq x\right\} = a + (1-a)(1-e^{-\theta x}) \qquad (4)$$

where "a" is the probability of no runoff, and θ is the inverse of the mean daily runoff on days with runoff during summer or the total seasonal runoff for each winter season (fig. 3). The parameters "a" and θ are functions of the rainfall amount for the daily runoff distributions.

The simulation procedure, involving the exponential function, consists of generating a random number between 0 and 1 from a uniform distribution to determine if runoff occurred on days with precipitation.

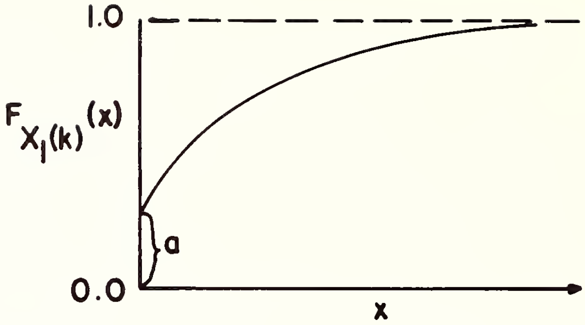

FIGURE 3.--Distribution function $F_{X_{1(k)}}(x)$.

If it did occur, another random number between 0 and 1 was generated and transformed to determine the amount of runoff according to equation 4.

Another method of simulating daily runoff is to compute the probability of no runoff, given the amount of precipitation, and then, if there was runoff, to generate the ratio of daily runoff to rainfall by sampling from the beta density function on days with runoff. The beta density function, which is often used when the random variables are proportions, is

$$f_U(u) = \frac{(\alpha+\beta+1)!}{\alpha!\beta!} u^{\alpha}(1-u)^{\beta} \qquad (5)$$

where U is the ratio of runoff to precipitation, with a range from 0 to 1, and parameters α and β are both greater than 0. Because of the nature of precipitation-to-runoff relationships, α was assumed to be 0. The distribution function for $\alpha = 0$ is

$$F_{U(k)}(u) = P\left\{U_{(k)} \geq u\right\} = 1-(1-u)^{\beta+1} \qquad (6)$$

The simulation procedure involving the beta function is that a random number between 0 and 1 is generated from a uniform distribution. If this number is greater than the probability of no runoff on days with precipitation, the days are assumed to be runoff-producing days. If there is runoff, a random number between 0 and 1 is generated from a uniform distribution, and the ratio of runoff to rainfall is computed by the transformation

$$U = 1-r^{\frac{1}{(\beta+1)}} \qquad (7)$$

where r is a uniformly distributed random variable between 0 and 1. Runoff is then computed by multiplying the ratio by the amount of rainfall. The β values in equations 6 and 7 are estimated from field data. Beta varies with daily precipitation amounts.

POND SIMULATION

Example Watershed

A 90-acre watershed near Newell, S. Dak., which has 15 years of precipitation and runoff information available, was used for testing this simulation model. This watershed was selected because it is close to the long-term precipitation station at the Newell Irrigation and Dry Land Field Station. The soils are derived from the Pierre Shale Formation and are thus very dense clays. These dense clays and the steep slopes are responsible for the more than 2 inches of annual runoff, as compared with 1 1/2 inches from other watersheds in the area.

The parameter values q_o, q_1, and λ were computed for 5-day sampling periods, beginning January 1 from the 63-year record at the Newell Irrigation and Dry Land Field Station. February 29 was included in the period for February 28. The 5-day parameter values were then fitted with a finite Fourier Series

$$F(x) = a_o + \sum_{n=1}^{13} \left(a_n \cos \frac{2n\pi x}{73} + b_n \sin \frac{2n\pi x}{73} \right) \qquad (8)$$

where a_o is the mean of the series, a_n and b_n are Fourier coefficients, and $x = 1, 2 \ldots, 73$.

The values obtained from the Fourier Series showed that each parameter had distinct seasonal patterns with numerous shorter term variations (fig. 4). These short-term variations would most likely be smoothed if longer meteorological records were available.

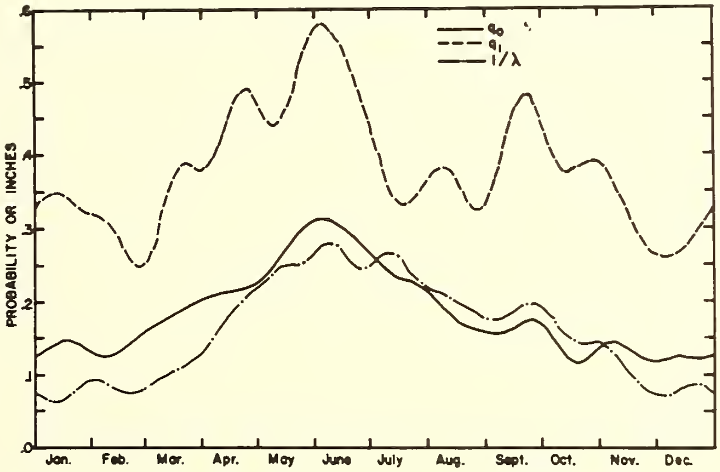

FIGURE 4.--Fourier Series fit to 5-day mean values of the parameters in the daily precipitation model.

The average of five 20-year daily precipitation simulations is summarized in table 1. These data indicate there was considerable variation between the simulated and the measured precipitation for some months, but that the average annual simulated precipitation varied less than 1 percent from the measured value. A statistical analysis of the monthly precipitation totals indicated that none of the simulated monthly totals were significantly different from the measured totals at the 5-percent level.

Pond Inflows

Snowmelt Runoff

The total runoff from the watershed for the winter months (November through April and May snowmelt) was used to compute a value of 1.004 for $\hat{\theta}$ in equation 4. Since at least a small amount of snowmelt runoff occurred during each of the 14 years, "a" was zero in this simulation. In this region, numerous small watersheds do not have snowmelt runoff

TABLE 1.--Measured and simulated precipitation and runoff

	Precipitation		Runoff		
				Simulated 4/	
Month	Measured 1/	Simulated 2/	Measured 3/	Exponential	Beta
	Inches	Inches	Inches		
January	.41	.40			
February	.36	.37			
March	.71	.75	1.00	0.82	0.82
April	1.60	1.43			
May	2.72	2.71	.54	.61	.41
June	3.06	3.25	.59	.52	.45
July	2.09	2.09	.09	.08	.12
August	1.32	1.40	.06	.13	.10
September	1.29	1.05	.04	.04	.06
October	.95	.92	.06	.01	.01
November	.53	.54			
December	.36	.39			
Total	15.40	15.30	2.38	2.21	1.97

1/ 63-year mean at Newell, S. Dak.

2/ Mean of five 20-year simulations.

3/ 14-year mean at Pond W-12.

4/ 20-year simulation.

annually, which would require an estimate of "a" at these locations. As can be seen from figure 5, the distribution function fits both the 14-year measured and 50-year simulated annual snowmelt runoff.

In the simulation, all of each year's snowmelt runoff was assumed to enter the pond on March 30 because data were insufficient for simulating monthly amounts. The snowmelt runoff for the 20-year simulation was 0.82 inch, which was 0.18 inch less than the measured amount (table 1).

Rainfall Runoff

Two techniques were used to simulate summer runoff. For the first, it was assumed that the conditional distribution of runoff, given the amount of precipitation, was distributed by equation 4 when both "a" and θ were functions of the amount of rainfall. The parameters $\hat{a}$ and $\hat{\theta}$ were first computed for rainfall classes of 0 to 0.25 inch, 0.26 to 0.75 inch, and 0.76 and greater. Runoff simulated, using these distributions, was less than that observed during May and during the drier months of July through October. Because of this discrepancy, data were grouped during May through June and July through October. These data groupings resulted in better estimates of monthly and seasonal runoff. Table 1 shows that the simulated monthly runoff differed from the measured runoff by as much as

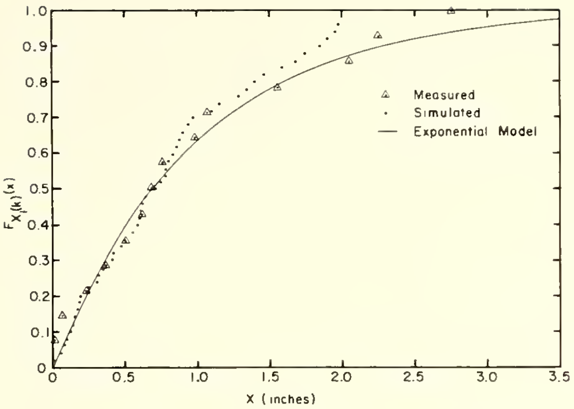

FIGURE 5.--Distribution function of annual snowmelt runoff.

0.07 inch for May, June, and August. The total simulated runoff for May through October was within 1 percent of the measured runoff.

The second method of simulating runoff depended on the assumption that the ratio of runoff to rainfall, given that runoff was greater than zero, could be adequately described by the beta function, with parameter α equal to zero and the parameter β a function of the amount of precipitation. A check of the data from the watershed under study indicated the values of α vary between -0.5 and +0.5, which suggests that the assumption of $\alpha = 0$ is valid. The Kolmogorov-Smirnov test of goodness of fit indicated that the measured and simulated cumulative distribution functions were not different at the 5-percent level for the 0.26- to 0.50-inch and 0.51- to 0.75-inch precipitation groups (6). This test also indicated that the assumption of $\alpha = 0$ is valid.

The probability of no runoff was also assumed to be a function of the amount of precipitation. The empirical linear relationships shown in figure 6 were used in the simulation. As the figure indicates, separate curves described the conditions for May through June and July through October. Figure 6 also shows that the simulation fitted the curves very well except for higher amounts of precipitation. This discrepancy is most likely due to the small number of events in these precipitation groups.

The empirical relationship between β and the daily precipitation is shown in figure 7. The plotted values of β were computed from the grouped rainfall data, using the method of moments estimator

$$\hat{\beta} = \frac{1}{\bar{u}} - 2 \qquad (9)$$

where $\bar{u}$ is the mean ratio of rainfall to runoff.

Table 1 shows that the 20-year simulation underestimated the monthly runoff for May, June, and October and somewhat overestimated the monthly runoff for July, August, and September. A statistical analysis indicated that the simulated monthly totals for May and June were not significantly different from the measured amounts at the 5-percent level. No statistical test was conducted to test the other months because of the short record.

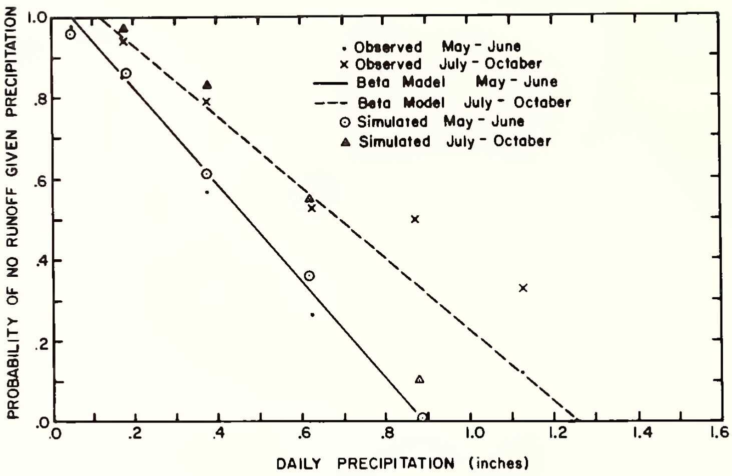

FIGURE 6.--Probability of no runoff, given that there was precipitation.

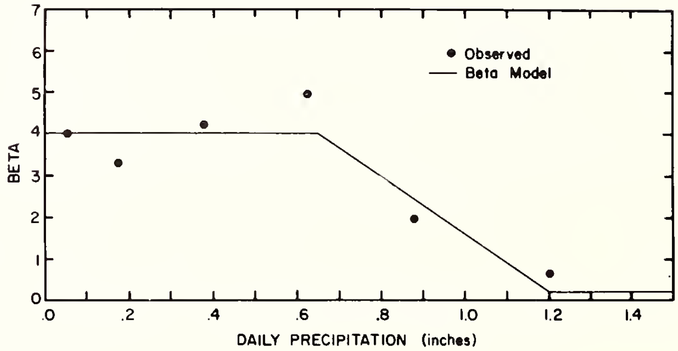

FIGURE 7.--β value used in beta model.

Rainfall on Pond Surface

Pond surface area had to be computed to estimate both the evaporation volume and the contribution to storage by rainfall on the pond surface. A third-order polynomial equation relating $\frac{\text{pond surface area}}{\text{maximum surface area}}$ to $\frac{\text{pond volume}}{\text{maximum volume}}$ was computed from 16 pond surveys in the Newell area. The equation is

$$S_* = 0.0036 + 1.844V_* - 1.886V_*^2 + 1.010V_*^3 \qquad (10)$$

where:

$$S_* = \frac{\text{Pond surface area (acres)}}{\text{Maximum surface area (acres)}}$$

$$V_* = \frac{\text{Pond volume (acre-feet)}}{\text{Maximum volume (acre-feet)}}$$

As shown in figure 8, equation 10 also fits data from seven ponds in northeastern Montana, which suggests that the equation may be used in regional simulation programs.

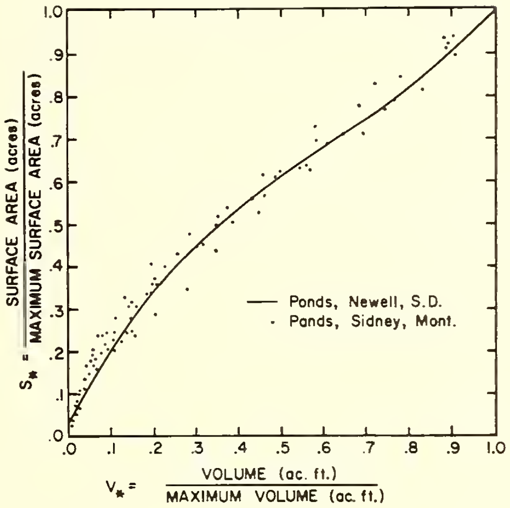

FIGURE 8.--Relationship between pond surface area and pond volume.

Pond Outflows

Evaporation

Daily evaporation was estimated by fitting a finite Fourier Series of 5-day sampling periods to 16 years of Class A pan evaporation data from the Newell Irrigation and Dry Land Field Station (fig. 9).

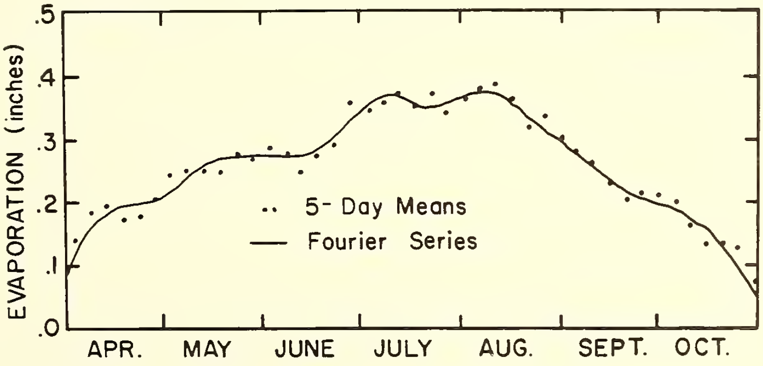

FIGURE 9.--Fourier Series fit to 5-day mean Class A pan evaporation, Newell, S. Dak.

Some of the small variations in the Fourier Series curve would no doubt be smoothed considerably with a longer record. The daily pan evaporation was then multiplied by 0.7 to estimate daily pond evaporation.

Livestock Use

In the simulation, livestock use, Y_3, was assumed to be at a constant rate throughout the grazing season (May 1 through September 30); livestock use the rest of the year was assumed to be zero. The daily use of 0.003 acre-feet was estimated to be about 10 gallons per day per head for 100 head of cattle. The grazing season length can be adjusted by changing its starting and ending dates. The daily water use can be varied in the program by changing the functional relationship.

Seepage

Daily seepage in acre-feet per day was estimated from a third-order polynomial, which had been fitted to information from Pond W-12. A general regional seepage rate function is not available. However, a study, being conducted at Sidney, Mont., is attempting to physically describe pond seepage rates, which should lead to a pond seepage function that will aid in regional pond simulation models.

POND DESIGN

To demonstrate the utility of the simulation approach to pond design, consider the following situation:

A rancher in western South Dakota wishes to supply water to 100 cattle during a grazing season from May 1 to October 1. We assume that the value of the water in alternative use is zero.

A 20-year simulation was run, using the exponential distribution to simulate runoff from rainfall. Search techniques were used to find the minimum pond sizes that would allow the pond never to be dry or would allow it to be dry for 1 percent of the days during the grazing season.

The simulation suggests that a 1.3-acre-foot pond is sufficient when no volume is lost because of sedimentation and the pond is not allowed to be dry during the grazing season (table 2). When the pond was allowed to be dry 1 percent of the total grazing season, the pond size was reduced 0.2 acre-foot. This reduction cannot be justified in western South Dakota because it would cost approximately $17 a day

TABLE 2.--Simulated pond size with the pond not dry and with the pond dry 1 percent of the days during grazing season

Simulation	Pond size 1/	
	Pond not dry during grazing season	Pond dry 1 percent of days during grazing season
	Acre-feet	Acre-feet
W-12	1.3	1.1
W-12 lined	1.2	1.0
W-12 lined and covered	.30	.24

1/ 20-year simulation.

(about $500 over 20 years) to haul water for 20 miles. Generally, increasing the pond 0.2 acre-foot would cost less than $100.

With a lined pond, the minimum pond volume was reduced by only 0.1 acre-foot. This volume decrease would not justify lining (2); however, the cost of lining a pond may be justified at other sites where seepage rates are much higher.

Simulating both evaporation and seepage control reduced the minimum pond volume approximately 1 acre-foot. Even with the reduced construction costs of a smaller pond, the reduced pond volume would not justify the cost of lining and covering a pond with a material, such as butyl, at this particular site.

Pond simulation programs can provide information other than just the optimum pond volume. Table 3 indicates the amount of spillway flow and the volume of seepage and evaporation.

TABLE 3.--Information from a 20-year simulation using the exponential runoff model with no seepage or evaporation control and no allowable days with a dry pond

Year	Precipitation	Runoff	Spill	Evaporation	Seepage
	Inches	Acre-feet	Acre-feet	Acre-feet	Acre-feet
1	17.27	14.52	12.25	2.33	0.28
2	15.17	16.67	15.21	2.07	.23
3	18.52	27.91	25.48	2.32	.27
4	11.29	11.98	10.93	2.11	.22
5	17.50	19.30	16.80	2.17	.20
6	12.31	11.09	9.12	2.27	.22
7	16.42	21.74	19.23	2.36	.25
8	13.48	9.53	8.58	1.89	.17
9	17.79	15.46	13.43	2.12	.15
10	15.84	28.29	25.45	2.31	.23
11	12.68	4.16	2.74	2.16	.21
12	16.58	22.82	20.38	2.28	.22
13	15.56	10.77	8.70	2.26	.23
14	16.61	25.73	23.28	2.33	.26
15	10.47	2.81	.41	2.24	.27
16	14.98	14.05	13.12	2.12	.22
17	17.19	12.42	10.64	2.09	.17
18	12.60	20.35	18.12	2.15	.18
19	13.68	25.72	23.17	2.26	.22
20	14.09	17.79	15.53	2.28	.24
Mean	15.00	16.65	14.63	2.21	0.22

The data can also be a guide to the annual precipitation and runoff distributions. Annual spill volume can be included in the spillway plans and, if spillway construction costs are critical, the program can provide daily flows. The quantity of water lost through evaporation and seepage is always of interest when downstream water use is considered. This pond has an average evaporation loss of 2.21 acre-feet, which is about 10 times the seepage loss. The seepage loss under most soil conditions would be considerably higher.

The simulation approach also allows the evaluation of storage loss due to sediment deposition and its affect on pond design.

CONCLUSION

This paper shows that simulation procedures can be used in stock pond design. The Markov Chain-Exponential model described daily precipitation amounts very well, indicating that this model will be useful when regional model parameter values are available.

The exponential model is a good stochastic description of annual snowmelt runoff (fig. 5). Either of the two stochastic models, exponential or beta, describing the relationship between daily precipitation and runoff, can be used in stock pond simulation studies. The 20-year simulation results suggest that the exponential model generated monthly values closer to the observed than the beta model (table 2). This may apply generally, or it may have been due to the random numbers generated.

Of the stock pond outputs, seepage loss is probably the most difficult to describe because of soil variations. A study underway at the Northern Plains Soil and Water Research Center in Sidney should provide data to solve this problem.

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DESERT STRIP FARMING--COMPUTER SIMULATION OF AN ANCIENT WATER HARVESTING TECHNIQUE [1]

George C. A. Morin and William G. Matlock [2]

INTRODUCTION

During most of recorded history, man has relied on plants to supply his food and fiber requirements. The supply of plant materials needed to fulfill these requirements is dependent upon the amounts of solar energy, nutrients, and moisture available for plant growth. Deficient water resources have been the limiting factor in the development of intensive crop production in arid and semiarid regions of the world. In Arizona, for example, water is stored behind large dams and is transported long distances overland or is mined from existing ground water supplies in order to maintain crop production. For Arizona to continue using and expanding these water supply methods, large inputs of energy will be required. The multiplication and collection of local runoff on nearby cropped areas offers an alternative and little used means of meeting crop water requirements. Only minimal inputs of energy are required to collect and direct the runoff water.

Water harvesting is the collection of local runoff to augment the existing water supply. Desert strip farming uses water harvested from a collector area to help supply the moisture requirements of a cultivated crop on a smaller farmed area (fig. 1). Water harvesting techniques,

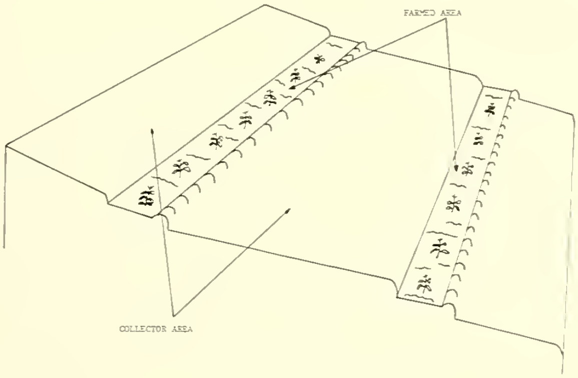

FIGURE 1.--Diagram showing desert strip farming concept.

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similar to desert strip farming, were used by inhabitants of the Negev Desert of the Middle East prior to the time of Christ (2). Water harvesting was also used by the native Indian population of northern Arizona 1,000 years ago and is still used to a limited extent today.

A field study of growing grain sorghum was made in southern Arizona, using only moisture obtained by direct precipitation and from adjacent untreated water collection areas. The yields obtained from the field study were compared with the yields obtained using normal irrigation farming techniques in southern Arizona. In addition, a mathematical model of a crop growing under desert strip farming conditions was solved using a digital computer, and yields obtained from the model were compared with yields from the field tests. After the model was calibrated, actual rainfall data for the years 1900-72 were used in the model to predict the long-term success of desert strip farming in southern Arizona.

FIELD TESTS

To test the validity of the desert strip farming concept, small cultivated plots and rainfall collector areas were constructed at Atterbury Watershed, approximately 27 km southeast of Tucson, Ariz. The plots are located near the headwaters of Atterbury Wash in an area where stock raising is the predominant economic activity. The topsoil in most of the cultivated area is a clay loam with the top of a caliche layer 1.3 to 1.7 m below land surface. The collector areas had a thin stony topsoil with the top of a caliche layer within 0.5 m of the land surface. The plots were fenced to protect the crop from livestock and other animals. The collector areas were left in their natural state except for the construction of earthen dikes, which directed the runoff water toward the cultivated plots. Cattle were allowed to graze in the collector areas. Soil moisture of both the collector areas and the cultivated plots was monitored with gypsum blocks and gravemetric samples.

Short-season grain sorghum was chosen as the first test crop because of the close correlation between its moisture needs and Tucson's summer rainfall distribution pattern (fig. 2). Grain sorghum has an average yield of about 4,500 kilograms of grain per hectare (kg/ha) under irrigation in the Tucson area. The lower elevations of the Tucson Basin, such as Tucson and Atterbury Watershed, normally receive about 140 mm of rainfall during the summer rainy season of July, August, and September. Grain sorghum requires about 570 mm of moisture to mature completely. Thus, a minimum of about four times the amount of water supplied by the average rainfall is required for crop development.

During the 1970 summer growing season, a 40-ha catchment area was used to supply runoff water for three 0.4-ha plots, giving a collector area to farmed area ratio of 33:1. The volume of runoff water from the collector area was measured with a H-flume, and precipitation was monitored by a rain gage network. There was 190 mm of precipiation, and a total of 530 mm of runoff was applied to the farmed area. The volume of runoff was too large to be handled by the dikes surrounding the cultivated plots, and reconstructed smaller collector areas were used in subsequent years. The total moisture supplied to the crop was approximately 720 mm. Soil moisture measurements and determinations indicate that the crop moisture requirements were not completely satisfied during part of August. The actual yield for short-season grain sorghum, planted at a population rate of 25,000 plants per hectare, varied between 800 and 2,300 kg/ha when harvested from individual rows.

During the 1971 growing season, a 12-ha collector area was used to supply runoff water for a single 0.8-ha plot, giving a collection area to farmed area ratio of 15:1. The volume of applied runoff water was

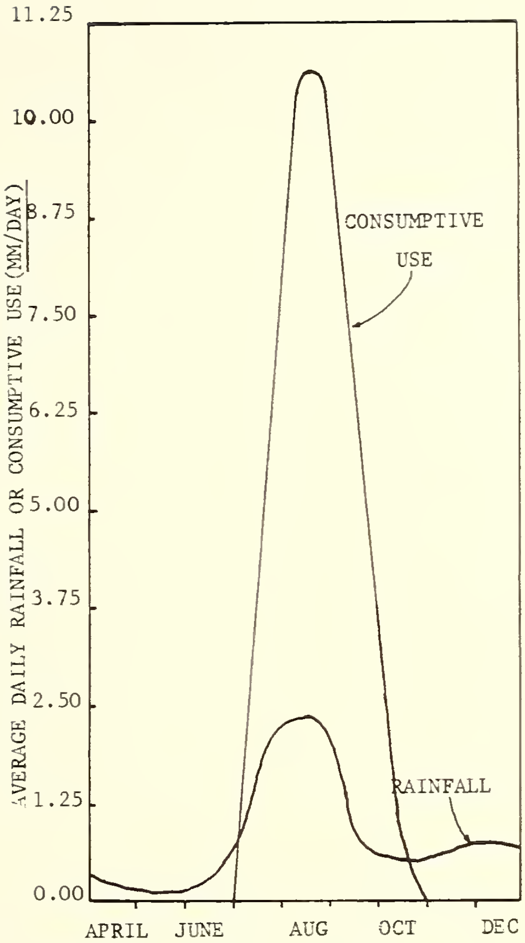

FIGURE 2.--Potential consumptive use and normal precipitation distributions.

estimated to be 390 mm from precipitation totaling 246 mm; thus, the total moisture supplied to the grain sorghum was estimated at approximately 640 mm. Soil moisture measurements in the field indicate that in most of the cultivated field the crop moisture requirements were satisfied during the entire growing season. In addition, the measurements show that soil moisture conditions were satisfactory during the seedling state of the crop. However, there was too much slope to the field, and there were isolated high spots. As a result, insufficient soil moisture was available to the crop in some parts of the field. and the actual yield ranged from 800 to 4,400 kg/ha.

In an attempt to more evenly distribute runoff water during the 1972 growing season, the 12-ha collector area was divided into two 6-ha areas. In addition, the farmed plots were completely releveled and divided into two 0.4-ha plots. Thus, the collector area to farmed area ratio remained at 15:1. To obtain a more accurate estimate of the runoff totals, water stage recorders were installed in each of the cultivated plots. The total volume of applied runoff water was estimated at 220 mm from precipitation totaling 137 mm; thus, the total moisture supplied to the grain sorghums was estimated to be 360 mm. This amount of moisture is insufficient to supply the moisture required by short-season grain sorghums. Soil moisture determinations indicate that sufficient soil moisture was available for only 1 week during the entire growing season. In addition, the measurements show very poor soil moisture conditions immediately following the seedling stage. The actual yield varied between 0 and 1,100 kg/ha (table 1).

TABLE 1.--Actual yields of grain sorghum at Atterbury Watershed during the 1970, 1971, and 1972 growing seasons

Year	Rainfall	Yield	
		Range	Average
	Mm	Kg/ha	Kg/ha
1970	190	800-2,300	1,600
1971	246	800-4,400	2,600
1972	137	0-1,100	500

During 1973, attempts were made to grow squash, watermelon, okra, and cucumbers. The physical arrangement of the collector areas and cultivated plots was the same as during the 1972 growing season. Soil moisture conditions were excellent in early June, following a 42-mm precipitation event. Germination was satisfactory; however, heavy loss of seedling plants occurred as a result of damage by rabbits and small rodents. In addition, only an additional 12 mm of precipitation fell during the last half of June and all of July and August. Thus, only five squash plants survived, and these did not bear fruit.

MODEL DEVELOPMENT

To better understand how crop moisture requirements can be satisfied by the water harvesting method of irrigation, several computer models, which simulate this irrigation system, were developed. The initial program was developed to determine the most successful crop and ratio of collector area to farmed area for any region of known hydrologic and soil characteristics. The model was calibrated for the Tucson Basin area using the data collected during the 1970, 1971, and 1972 growing seasons, with short-season grain sorghum as the test crop. After calibration, the model was used to predict the success of the desert strip farming system for several collector area to farmed area ratios based on 76 rainfall data sets for several weather stations in the Tucson Basin for 1900-72.

The logic of the main model is illustrated by the block diagram in figure 3. Precipitation falling on the collector area produces runoff, which, when added to the direct rainfall, makes the total available moisture supply for the farmed area. Immediate losses of moisture are to evaporation and excess runoff. Infiltration provides soil moisture for the layers 1 to n. Excess soil moisture is lost as deep percolation. Extractions from the soil moisture reservoir are by evaporation prior to crop germination and by evapotranspiration (evaporation from the soil surface and transpiration by plants) after germination, The accuracy of the model in representing the real system is limited by the equations

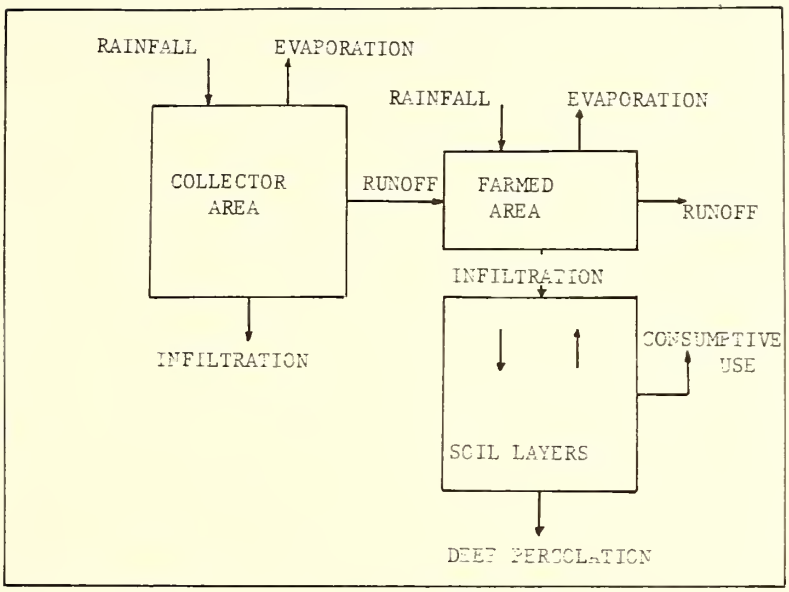

FIGURE 3.--Block diagram of desert strip farming concept.

that describe the individual moisture transfer process, by the accuracy of the yield versus actual consumptive use equation, and by the various parameters used in the equations. The equations that describe the moisture transfer process also describe the convervation of matter and are arithmetic in nature. The mathematical model is basically a bookkeeping operation.

The necessary inputs to the model include: (1) a rainfall versus time distribution, obtained from actual data or from probability of occurrence data; (2) a runoff versus rainfall and antecedent soil moisture relations in the collector area; (3) an evaporation versus temperature and cropped area soil moisture relationship; (4) soil data including infiltration characteristics, depth, layering, and water holding capacity; and (5) crop data including drought tolerance in the seedling and maturing stages of plant growth, potential consumptive use requirements in time and space, and actual yield versus actual consumptive use by the crop. All of these input data will not be available in most practical situations and estimates will have to be used.

The basic model has gone through several stages of development (4). The present model begins on a date coincident with the beginning of the crop season and continues to cycle repeatedly through a set of calculations until the crop matures, dies, or has grown for an arbitrarily long period without maturing or dying. The cycle is based on a 1-day period.

An optimum planting date is assigned to each crop to be tested. If sufficient precipitation has not fallen prior to this date, the crop is planted in expectation of rainfall in the immediate future. If sufficient precipitation occurs prior to this date, then the crop is planted as soon as field conditions are satisfactory. Once the crop is planted, it may grow and mature, die as a result of drought, or not fully develop as a result of drought. For each day, the program determines the moisture input, actual consumptive use by the crop, the change in the soil moisture storage status, and moisture outputs.

Two drought tolerances are specified for each crop. If the seedling stage tolerance is exceeded, the crop dies. If the maturing stage tolerance is exceeded, plant development is retarded. However, the program continues on the assumption that some economic value can be derived from the stunted crop.

The soil moisture available for crop development in any day is the water stored in the root zone plus the additional moisture from rainfall and runoff, which remains in the cultivated area. If this amount of moisture equals or exceeds the potential consumptive use, then the actual consumptive use is the potential use with any excess being stored for use in succeeding days. If the available soil moisture is less than the potential use, then the actual use equals the existing soil moisture. If the amount of water added to the soil system exceeds that which can be stored in the root zone, it is lost as deep percolation. After the crop matures, the yield is calculated as a function of the actual moisture used by the crop.

Outputs from the computer model include: (1) soil moisture balance, including moisture inputs from precipitation and runoff, moisture losses resulting from excess runoff and deep percolation, and the moisture status of each soil layer at the beginning and end of each day; (2) the actual consumptive use for each day; (3) a listing of the days when soil moisture was deficient and when drought tolerance was exceeded; and (4) the actual yield of the harvested crop. The program is designed so that it can be used with several different collector area to farmed area ratios to obtain the ratio needed to give the most efficient production.

Other computer models are being developed to give a more accurate description of the soil moisture conditions in a cropped soil. These programs include one-dimensional linearized (_1_, _7_) and finite difference (_3_, _6_) solutions to the moisture flow equation with a moisture withdrawal function. The models require considerably more computer time than the basic bookkeeping program described above. As a result, even after complete development of these programs, they will be primarily used to calibrate the initial program rather than being incorporated into it.

COMPARISON OF PREDICTED AND ACTUAL RESULTS

Data collected from the 1970, 1971, and 1972 field experiments at Atterbury Watershed were used to calibrate the basic computer model (_5_). During the 1970 growing season, actual yield averaged 1,600 kg/ha, while the calibrated model predicted 1,900 kg/ha. In 1971, the actual average yield was 2,600 kg/ha versus 2,100 kg/ha predicted by the computer model. In 1972, the figures were 500 and 800 kg/ha, respectvely. These data (table 2) tend to indicate that the model predicts slightly on the low side when soil moisture conditions are good and on the high side when moisture conditions are poor. The major cause of this discrepancy is probably due to the inability of the yield function to take into consideration when a soil moisture deficiency occured. The authors feel that moisture deficiencies in the seedling stage will affect yield more than moisture deficiencies in the maturing stage.

At the present time, the information required to adjust the yield function has not been incorporated into the program because necessary details are lacking. Another problem associated with the model is that it indicates the soils is drying out more rapidly after a precipitation event than the actual field data show. This is due to the fact that the computer model ignores redistribution of soil moisture after a precipitation event. The analytical and finite difference soil moisture flow models being developed should help alleviate this problem.

TABLE 2.--A comparison of actual and predicted yields of grain sorghum at Atterbury Watershed during the 1970, 1971, and 1972 growing seasons

Year	Average yield	
	Actual	Predicted
	Kg/ha	Kg/ha
1970	1,600	1,900
1971	2,600	2,100
1972	500	800

PREDICTIONS WITH 1900-72 DATA

Precipitation records from several weather stations in the Tucson Basin were tabulated for 1900-72. The basic desert strip farming computer model was then used to obtain predicted yields of grain sorghum as kilograms per hectare for several collector area to farmed area ratios for these records (table 3).

Relationships showing maximum yield versus collector area to farmed area ratio, average yield versus collector area to farmed area ratio, and years with crop failure versus collector area to farmed area ratio can be compiled from table 3. The data indicate that for the Tucson Basin desert strip farming is noncompetitive with normal, irrigated, short-season grain sorghum; however, significant production does occur. In addition, the data show that for collector area to farmed area ratios greater than 12, only relative small increases in yield should be expected and that with larger ratios, chances of crop failure are not appreciably reduced.

Plots of predicted yield versus collector area to farmed area ratio for selected, but typical, years,illustrate that yield is not a direct function of total precipitation. For the years 1914 and 1955, rainfall totals were 237 and 236 mm, respectively; however, for a collector area to farmed area ratio of 12, the yields were 1,800 and 2,500 kg/ha, respectively. For 1936, which had a total precipitation of 196 mm, the yield was 2,500 kg/ha for a ratio of 12. These results can be explained in part by noting that the model predicts that for 1914 there is a soil moisture deficiency between the 26th and 75th days of growth (table 4). During 1936 and 1955, soil moisture conditions were more satisfactory in this same time period. Thus, although 1936 had less precipitation than 1955, the timing of the rainfall events was better and yields were equal to those of 1955. In 1914, use of moisture from precipitation was even less efficient than for 1955 (table 4).

TABLE 3.--Predicted yields versus collector area to farmed area ratio for selected years

Year 1/	Rainfall	Yield of grain per following collector area to farmed area ratio			
		8	12	16	20
	Mm	Kg/ha	Kg/ha	Kg/ha	Kg/ha
1900 T	77	0	0	0	0
1910 T	183	1,300	1,300	1,300	1,300
1914 T	237	1,700	1,800	1,900	1,900
1920 T	119	500	900	1,100	1,500
1930 U	104	500	900	1,200	1,300
1936 T	196	2,200	2,500	2,700	2,800
1940 T	193	1,600	1,700	1,700	1,800
1950 C	169	1,600	1,800	1,800	1,900
1955 C	236	2,400	2,500	2,600	2,600
1960 C	129	1,000	1,200	1,400	1,600
1970 A	190	1,600	1,700	1,700	1,800
1971 A	245	1,900	2,000	2,100	2,200
1972 A	137	700	800	900	1,000
Maximum yield.		2,400	2,500	2,700	2,800
Average yield.		1,000	1,100	1,200	1,300
Years of crop failure. 2/		16	15	14	13

1/ Letter following year indicates name of weather station.

A, Atterbury Watershed

C, Campbell Avenue Experimental Farm

T, Tucson Weather Bureau

U, University of Arizona

2/ For all years and weather stations (76 data sets).

TABLE 4.--Crop moisture stress conditions for selected years
[Numbers without parentheses indicate that period of growing season with potential water use greater than 0.6 mm. Numbers in parentheses indicate the entire growing season]

Year 1/	Days with precipitation	Days with runoff	Days with 100% of required water available	Days with 50-99% of required water available	Days with 1-49% of required water available	Days with no water available
1955 C	20 (27)	11 (12)	34 (62)	2 (10)	12 (35)	1 (14)
1936 U	12 (26)	6 (11)	24 (62)	4 (12)	19 (34)	2 (12)
1914 T	16 (41)	6 (11)	10 (69)	6 (7)	30 (39)	3 (3)

1/ Letter following year indicates name of weather station.

C, Campbell Avenue Experimental Farm

T, Tucson Weather Bureau

U, University of Arizona

DISCUSSION

Desert strip farming is a method of increasing agricultural productivity in arid and semiarid regions of the world by using water harvesting to augment natural precipitation. A computer model was developed to predict the success of the method in regions of the world where rainfall patterns and soil characters are known or can be estimated. Data for the Tucson Basin indicate that for a collector area to farmed area ratio of 12 there will be significant production of short-season grain sorghum in 4 out of 5 years. The data also indicate that only small improvement in the success rate can be expected for larger collector area to farmed area ratios.

Field experiments at Atterbury Watershed support the validity of the model. The results of the field studies show that the soil moisture status at germination and immediately afterwards is an important factor in successful crop production. Both the model and field studies indicate that regardless of the collector area to farmed area ratio used, crop failures will occur. The model also indicates that the distribution of the rainfall in time and space may be more important than total rainfall, after a set minimum amount of precipitation has occurred, in determining the actual yield of short-season grain sorghum.

The experiment at Atterbury Watershed points up an advantage of leaving the collector area in its natural state so it can be used in its traditional manner, that is, livestock raising. If the crop is a failure, only a small amount of land is lost to the livestock raising activity. If a crop is produced, the collector area has helped provide the moisture for the crop as well as feed for the livestock.

Future project activities will include improvement of the soil moisture distribution and yield subroutines in the computer program, identification of other crops that can be grown with the desert strip farming system, and additional field tests.

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A COMPUTER MODEL FOR OPTIMIZING DESIGN OF IMPROVED CATCHMENT

J. L. Frith, R. A. Nulsen, and H. I. Nicol [1]

INTRODUCTION

In the wheatbelt of Western Australia, artificially improved catchments are used to increase inflow to farm dams. Roaded catchment is the main form of improvement, but bitumen sealing has been used.

Design standards for size of roaded catchment relative to the size of the dam were originally put forward by the Public Works Department (4) which recommended 4 acres per 1,000 cubic yards of dam capacity. Carder (1) and Carder and Spencer (2) modified this estimate to 6 acres of roading per 1,000 acres of dam capacity. These standards assume that dams will be filled and emptied once each year and are simply predictive estimates of the minimum likely annual yield from roaded catchment.

Ideally, design standards relating any type of catchment to dam capacity should take account of all three components of the system: inflow (comprising precipitation and runoff), storage capacity, and outflow (comprising seepage, evaporation, and drinking losses). Of these three components, inflow is the most difficult to predict by rational methods.

Natural catchments of farm dams are too large and variable and the proportion of falls of rain retained by them too high for the pattern of their hydrologic behavior to be usefully predicted from the only widely available relevant data--daily rainfall records. However, artificially improved catchments have relatively small areas, are more uniform, and retain less rainfall. Errors involved in predicting their behavior from daily rainfall records will be smaller. Useful predictions thus seem possible.

In the present study, a mathematical model of a stock water supply--comprising a dam, an improved catchment with a stated "effective threshold," [2] and a flock of sheep--has been constructed. The model is used to define rates of substitution of catchment area, dam capacity, and flock size that provide water for sheep at all times at Jerramungup 6/ in Western Australia, 360 km southeast of Perth.

THE MODEL

Inflow

Sixty years of daily rainfall records for "Jarramongup Homestead," a station 3 miles east of Jerramungup, were used to compute daily additions to storage. Rain falling directly on the stored water surface and on the dam batters was considered to be wholly transferred to storage. Rainfall on the catchment was adjusted for the discrete recording of continuous falls (5) 3/ and for threshold, to give daily volume of runoff--

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[1] District soil conservation adviser, Moora; research officer, Soils Division, South Perth (presently of Ontario, Canada); and biometrician, South Perth; respectively, Soil Conservation Service, Department of Agriculture, Western Australia.

[2] The catchment threshold is that part of a fall of rain that does not reach the dam. This obviously will vary between falls. The effective threshold is equal to the difference between the total volume of rainfall over the catchment and the total additions to storage divided by the number of individual falls, during the period being considered.

$$= P\ (1 + 0.0023\ T) - T$$

where P = daily rainfall in millimeters

T = catchment threshold in millimeters

Two threshold patterns were used: 2.5 mm on each day and 7.5, 6.25, and 5 mm on successive days of rain. The second pattern represented an arbitrary allowance for increasing antecedent soil moisture with successive days of rain.

The first pattern was chosen to represent the performance of a bitumen catchment. The second was taken to be safely above the effective threshold of the carefully constructed roaded catchment.

Storage

Dams had a square plan and batter slopes of 1 in 3. Depths were arbitrarily assigned as follows:

Volume in cubic meters	Depth in meters
750 to 1,000	3
1,250 to 2,500	4
3,000 and greater	5

At the end of each day of inflow, or at the end of a dry period, a new surface area resulting from net flow was calculated. The one surface area was used to calculate volume loss due to evaporation in the ensuing dry period. Dry periods were terminated on the last day of the month and a new period commenced.

Outflow

Outflow consisted of drinking by sheep and evaporation. Outflow values were varied monthly as shown in table 1.

TABLE 1.--Values used in the model of daily rates of loss from storage by drinking and evaporation

Month	J	F	M	A	M	J	J	A	S	O	N	D
D 1/	3.4	3.2	2.5	1.7	0.9	0.2	0.0	0.2	0.9	1.7	2.5	3.2
E 2/	5.9	5.2	4.1	1.5	2.1	1.4	1.3	1.4	2.3	3.2	4.3	5.8

1/ D = volume drunk in liters per head per day.

2/ E = depth of evaporation from dams in millimeters per day.

3/ This source notes that 11.5 percent should be added to 9 am to 9 am daily rainfall records in estimating the size of unrestricted 24-hour falls. In the present study, full allowance of 11.5 percent was made for a threshold of 12.5 mm, and this was decreased proportionately as the threshold approached zero.

Evaporation for each month was obtained by interpolation between isopleths of monthly evaporation published by the Commonwealth Bureau of Meteorology. These are based on values of saturation deficit combined with evaporimeter measurements at 70 centers throughout Australia. No allowance was made for seepage.

Operation

Combinations of catchment area, dam capacity, and sheep flock size were set up. The period of accounting was 720 months starting on January 1, 1907. On this day dams were empty. When the volume of stored water equaled or exceeded 0.25 m^3 per sheep and depth of stored water equaled or exceeded 20 cm, sheep were introduced; that is, daily subtraction of volume drunk began. Sheep were removed when storage declined to either of the above levels.

The percentage of time for which the dam did not support the sheep and the maximum length of any period for which sheep were taken off and withheld were printed.

Increments of catchment were added or subtracted until the system was found that just managed to support the sheep continuously.

RESULTS

The lowest catchment areas found, which supported sheep, have been plotted against dam capacity for various flock sizes and for catchment threshold of 2.5 mm (fig. 1) and 7.5 mm (fig. 2).

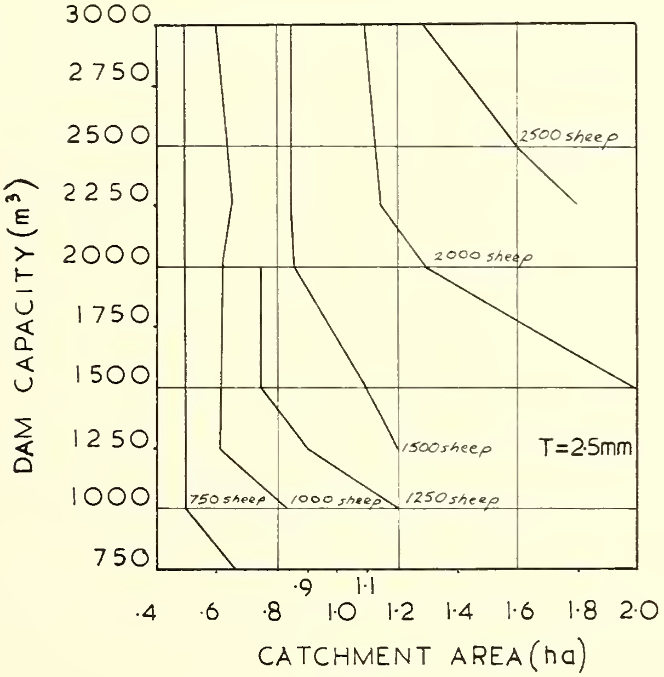

FIGURE 1.--Isoquants of dam capacity and improved catchment (threshold = 2.5 mm) at Jerramungup.

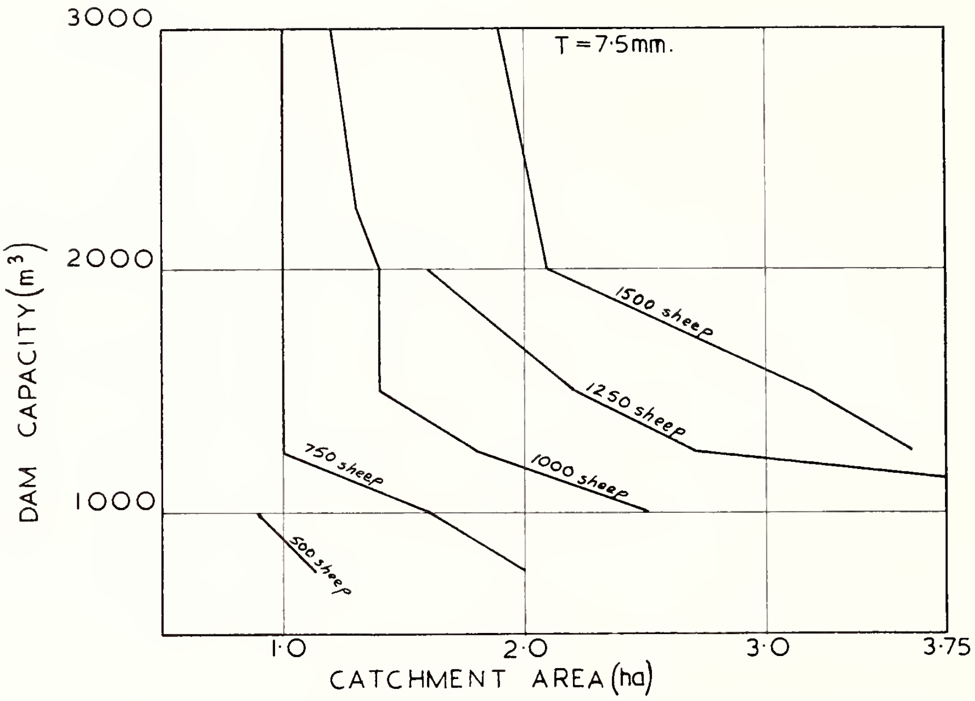

FIGURE 2.--Isoquants of dam capacity and improved catchment (threshold = 7.5 mm) at Jerramungup.

The relationship between dam capacity and catchment area is one of imperfect substitution. The isoquants 4/ are concave; there are minima of both capacity and area beyond which substitution cannot be made.

Minor departures from concavity are due partly to discontinuity in values of capacity and area, to differences in the arbitrary relation between dam depth and volume, and to vagaries in the operation of the model.

The isoquants can be used to find the least cost combination of dam and catchment that would have just provided for the sheep throughout the 60-year period.

For example, in figure 3, the 1,000 sheep isoquants for catchment thresholds of 2.5 and 7.5 mm are shown. In the case of 2.5 mm threshold, catchment sealing has brought the unit price to \$2,500/ha. Cost of storage is \$0.30/m^3. Thus, dam and catchment can be substituted at the rate of 8,333 m^3 per/ha without affecting total cost. The point where a line of this slope (isocost 5/), meets the isoquant tangentially indicates the least cost combination of catchment and dam that would have provided continuously for the sheep. This is a 1,250-m^3 dam and a 0.6-ha catchment.

The usual range of roaded catchment situations is represented on the 7.5-mm isoquant. Here isocosts are drawn representing catchment costs

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4/ Isoquants join combinations of inputs that yield identical output.

5/ Isocosts join combinations of inputs that have identical cost.

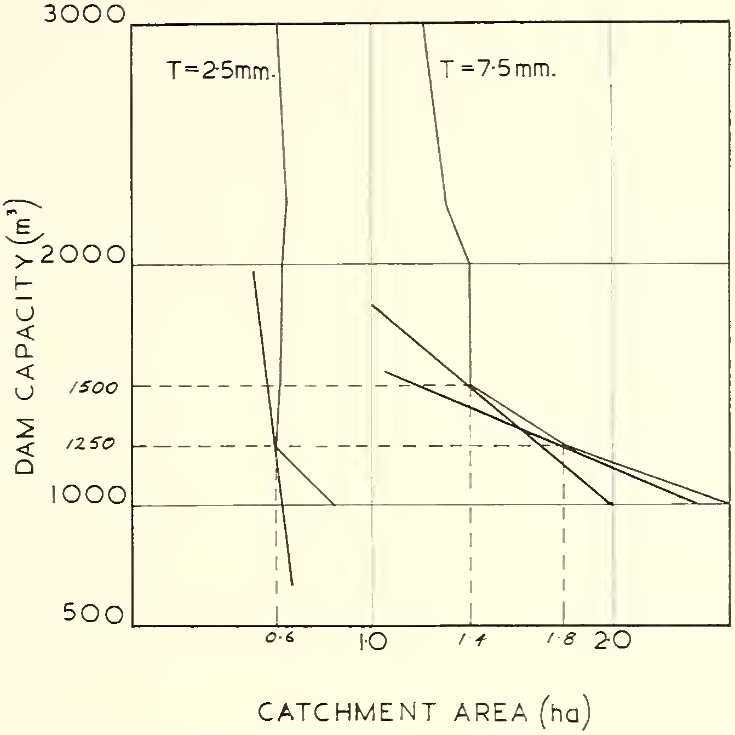

FIGURE 3.--The application of isocosts to isoquants to determine least cost combinations of dam capacity and catchment area for 1,000 sheep at Jerramungup.

of \$250/ha and \$125/ha and dam costs of \$0.30/m^3. The cheapest combinations that would have provided for 1,000 sheep are, respectively, a 1,500-m^3 dam with a 1.4-ha catchment and a 1,250-m^3 dam with a 1.83-ha catchment.

DISCUSSION

Validity of Model Components

Runoff

The simplifying assumption of a catchment threshold is the factor most open to challenge. Variation in rainfall intensity and sequential pattern and, on the catchment itself, in antecedent soil moisture, hydraulic conductivity, and conformation and extent of the catchment surface, all combine to make the relation between a depth of rain and the runoff it generates extremely variable.

Implicit in the notion of catchment threshold are the assumptions that (1) Over a period, the sequence patterns of factors affecting the rainfall-runoff relationship will be effectively repeated and that the excess of actual over calculated runoff will equal the shortfalls and (2) random distribution of shortfalls and excesses make it unlikely that the actual volume of storage will depart importantly from calculated volume.

Obviously, until the extent of variation in threshold, rainfall intensity, and catchment qualities is known, margins of safety must be arbitrarily applied in using information generated by the model.

Measurements have been made of daily rainfall on two roaded catchments and the volume changes in the dams which they supplied. 6/

On one, the total volume change over a 5-month period indicated an effective threshold of 3.5 mm. In the other, threshold for individual falls on the dry catchment ranged from 5.5 to 6.5 mm and on succeeding wet days from 1.3 to 4.2 mm. Its average effective threshold was 4.5 mm.

These measurements support common observation, which indicates that few daily rainfall events in excess of 5 mm fail to run water on properly constructed roaded catchments in most of the wheatbelt.

The value of 7.5 mm, chosen to represent the threshold of well-constructed, clay-covered roaded catchment, would seem to be safely above the achievable limits of practice.

Drinking

Few measurements of water consumption by normal paddock run sheep are available from other parts of Australia that are comparable with Jerramungup. Pierce (3) measured consumption by lactating ewes and their lambs in South Australia and found it to range from nil in July to between 6 and 8 liters per day for ewe and lamb in January. Weaned lambs on pasture in February consumed between 2 and 4 liters per day. Lightfoot and Fels 7/ experimented with consumption by sheep under different conditions of feed at Merredin and Wongan Hills in Western Australia. Under normal summer conditions, with ample dry pasture available, consumption was 0.4 to 0.6 gal/head/day (1.8 and 2.7 liters, respectively).

Observations of farmers who carted for sheep during the 1969-72 drought at Jerramungup were that although 4.5 liters/head/day was a figure frequently used in calculating requirements, careful storage in tanks and metering into troughs could reduce average daily use to 1.5 liters per day. Since the model accounted for evaporation, the drinking allowance of 3.4 liters/head/day for January appears ample. It is a matter of common observation that sheep do not drink when on green feed during the Western Australian winter.

Evaporation

Direct measurements of evaporation from any sort of water body are not available for the Jerramungup area.

Seepage

Seepage rates in farm dams vary from an extreme, indicating failure, to almost zero, within the order of volume change here concerned. Until seepage rates from individual farm dams can be readily measured, there seems little point in accounting for it in the model.

Use of the Model

Despite shortcomings, input data and model operation are more apt and less approximate than the data and methods hitherto used in Western Australia to prescribe design standards for improved catchment. In its present state, if applied to data from representative centers in the

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6/ Negus, T. R., personal communication.

7/ Lightfoot, R. J. and Fels, H. E. Water Requirements of sheep. Experiments in 1969/70. West. Austral. Dept. Agr., Sheep and Wool Branch. Unpub. rpt. 1971.

wheatbelt, the model offers a better basis for deciding catchment size in relation to storage and consumption.

The output data for Jerramungup demonstrate the ability of modest amounts of improved catchment to make supplies independant of natural catchments in the Jerramungup climate. This allows much greater flexibility in siting dams and a decrease in the volume necessary to fulfil a given need.

Some Implications for Public and Private Water Supply Policy

It is quite usual for Western Australian farmers to have a total dam capacity in excess of the Department of Agriculture's recommendation of a minimum of 6 yd^3 (approximately 4.6 m^3) per dry sheep equivalent where natural catchments are used. This represents a minimum outlay of approximately $1.40 per sheep. Where water is supplied at a farm boundary from a public reticulated scheme, outlay costs for an internal reticulation system are usually of the order of $4/ha. The concentration of sheep in much of the wheatbelt varies from less than two sheep per hectare to four sheep per hectare. Internal reticulation in the wheatbelt can thus cost from $1 to $2 per sheep. The cost to the State for extension of reticulated schemes for farms has varied between $25 and $50/ha of land served. Much of this is through land that carried 2.5 sheep per hectare or less. The total (public and private) outlay cost of large reticulated schemes thus varies between about $11 and $22 per sheep supplied.

The present study indicates that in the region of Jerramungup, it is likely that sheep could be supplied from dams and roaded catchments for an outlay of about $0.65 per sheep. In extreme cases, sealed dams and sealed catchments could be provided for about $4 per sheep. Jerramungup has a relatively low evaporation (annual average = 1,190 mm). An older version of the present model has been applied to data from Wongan Hills (annual average evaporation = 2,220 mm).

Indications are that considerably higher levels of storage and catchment would be required at Wongan Hills. These would entail outlay expenditures of $2 to $3.

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(2) ________ and Spencer, G. W.
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(3) Pierce, A. W.
1968. Studies on salt tolerance of sheep. VIII. The tolerance of grazing ewes and their lambs for drinking waters of the types obtained from underground sources in Australia. Austral. Jour. Agr. Res. 19: 589-595.

(4) Public Works Department of Western Australia.
1956. Roaded catchments for farm water supplies. West. Austral. Dept. Agr. Bul. 2393.

(5) Storm Water Standards Committee.
1958. Australian rainfall and runoff. Austral. Inst. Engin.

DISCUSSION

SESSION III, Part 1--Charles Staff, Chairman

H. QASHU: How do you calculate the "point-rainfall" sequencing?

G. MORAN: All rainfall data for 1900-69 are from the U.S. Weather Bureau records. Individual storm events for 1970-72 at Atterbury were broken up when determining runoff. It was assumed that the rain gage was representative of the entire watershed.

H. QASHU: How did you calibrate the model?

G. MORAN: The model is still being calibrated. The 1970-72 data are being used to try and get a handle on what to expect in yield. Once the model is calibrated, it will probably predict more yield in good years and less yield in bad years.

D. WOOLHISER: For desert strip farming, would there be any advantage in adjusting plant populations, depending on the soil moisture level at planting, or in thinning plants at a critical moisture level later in the season?

G. MORAN: We usually plant on the 27th of June. The soil is dry at this time. The first rains occur during the first week of July, and the field would be too muddy to plant. If more help were available, thinning would probably increase yields in low rainfall years.

SESSION III, Part 2--Charles Staff, Chairman

SEALING LEAKING EXCAVATED TANKS ON FARMS IN WESTERN AUSTRALIA

I. A. F. Laing [1]

INTRODUCTION

In the cereal and sheep area of Western Australia (receiving less than 750 mm annual average rainfall), approximately 74,000 excavated earth tanks are on approximately 14,000 farms. Most farms have some underground water, although some 4,500 farms rely entirely on water stored in excavated tanks for stock water supplies. The excavated tank is, therefore, an important structure on many farms.

In this paper, control of seepage from excavations is discussed. Throughout most of the cereal and sheep area, runoff seldom occurs during the summer and autumn months, and effective excavated tanks must hold water for at least 200 days. In this study, a leaking excavated earth tank is one from which more than 600 mm depth of stored water is lost by seepage in 200 days.

From farm water supply surveys conducted between 1967 and 1973, it has been shown that in most districts a small proportion (<5 percent) of all excavated tanks leak. [2] However, in some districts a much greater proportion of excavations leak (see fig. 1):

District:	Proportion of all dams that leak Percent
Badgingarra	50
Bindi Bindi	7
North Kalannie	43
Beacon-Bonnie Rock	6

In these districts, the leaking excavations are all constructed in soils formed in situ, and the original rock fabric can often be seen in the undisturbed soil. At Badgingarra, the problem occurs in the higher part of the landscape in the mottled zone of a laterite profile. Pepper [3] has studied the causes of high permeability in Badgingarra clays, and using the four soil properties (silt content, cation exchange capacity, exchangeable sodium, and iron in the silt fraction), he accounted for 95 percent of the variability in water level fall per day in excavated earth tanks.

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[1] Research officer, Soils Division, Department of Agriculture, South Perth, Western Australia.

[2] Farm water supply survey reports. Duplicated notes. Hollick, M. F. G., Badgingarra (1968); Laing, I. A. F., and Swarts, J. A., Bindi Bindi (1967); Laing, I. A. F., and Nelson, W. R., North Kalannie (1965), Beacon-Bonnie Rock (1966), Narembeen-Mt. Walker (1966), Holt Rock-Lake Varley (1966), and Pingaring (1966).

[3] Pepper, R. G. Properties of soils and seepage from small earth dams at Badgingarra, W. A. Thesis submitted for M. Sc. in Agriculture, University of Western Australia. 1973.

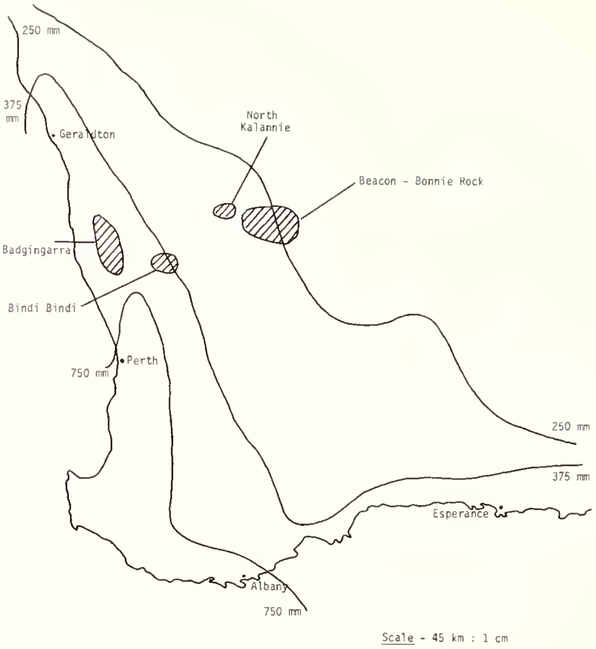

FIGURE 1.--Map showing area where leakage from excavated tanks is a problem and annual rainfall isohyets.

At Bindi Bindi, North Kalannie, and Beacon-Bonnie Rock, the problem generally occurs at depths greater than 3 m and is characteristically a problem in pallid zone material of acid reaction (pH 5 in soil and water in the ratio of 1:5). These districts of higher risk than normal are all areas where underground water is generally available, although the costs of developing underground supplies can be considerably more than developing excavated tanks and improved catchments. The cost of developing an underground supply at Badgingarra is approximately $A12,000. (One bore, 150 m deep, to supply 80,000 liters/day containing approximately 1,500 mg/l total soluble salts.)

The cost of developing underground water supplies in the other three areas is lower due to the water being shallower, but the daily supply per bore or well is poorer (average 10,000 l/day) and the water quality is poorer. In both situations, the total costs to supply the whole farm with stock water are comparable.

Although underground water supplies are available throughout a district, such supplies may not be available on every farm. For example, in the Beacon-Bonnie Rock district, 75 percent of farms have an underground supply, and the other 25 percent rely entirely on excavated tanks.

There is likely to be considerable expansion of agriculture in Western Australia in the next 20 to 30 years, and conservative estimates suggest an expansion of stock numbers from 40 million dry sheep equivalents to 95 million dry sheep equivalents by 2000 AD. 4/ Half of the increase in stock numbers will occur in new areas yet to be alienated, and half will occur due to expected intensification of the livestock industry on existing cleared areas. The number of excavated tanks will increase proportionately, and the percentage of tanks that leak will be the same or even greater than now because the better sites have been

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4/ Hogstrom, A. W. Livestock number projections. Department of Agriculture, South Perth. Duplicated notes 1972.

utilized on the present cleared areas, and poorer sites are likely to be developed in the future. Thus, the sealing of leaking excavations will be of increasing interest.

Economics of Sealing Leaking Excavated Tanks

The cost of sealing per volume of water stored, varies with the capacity of the tank. As capacity increases, the wetted surface or surface requiring sealing increases, but at a decreasing rate. (See table 1 in Appendix at end of report.) Treatment of a large tank is therefore cheaper per cubic meter than for a small tank.

The economics of sealing treatments are also dependent on the costs of an alternative supply of water. The alternatives to sealing a leaking tank are usually either a replacement excavated tank on another site or an underground supply. On most farms, an alternative site can be found for an excavated tank, and where this alternative exists the upper limit to the cost of sealing treatments ($\$A/m^2$ of surface to be sealed) is given in table 1. Where an alternative tank site does not exist, the maximum allowable expenditure on a sealing treatment is likely to be much greater, and the results of the research reported in this paper may be applicable in such cases.

For a sealing technique to be applicable to most excavated tanks in the Western Australia cereal and sheep areas, the following criteria must be met:

- Effective life of many years.
- Maximum tolerable seepage loss of 600 mm/200 days.
- Applicable on 3:1 slopes.
- Resistant to prolonged exposure to solar radiation, high summer temperatures (>37° C), and occasional high winds (>70 km/hr).
- Conducive to field patching.
- Unaffected by widely fluctuating seasonal water levels.

The cost limitations referred to previously must also be considered.

The stability of the treated layer, the ease of installation, and the need for maintenance also warrant consideration.

METHODS AND MATERIALS

Assessment of Rate of Seepage

A basic water budget for an earth tank can be written in equation form, as follows:

Change in Stored Volume (ΔV)

= (Runoff from catchment, and batters + rainfall on water + seepage in)

- (Evaporation + consumption + seepage out)

If a rain-free period is chosen for the study, animals are excluded from the system, and sites are chosen such that seepage in is unlikely. Then, the following simplified water balance equation can be written:

Change in stored volume (ΔV)

= Evaporation + seepage out.

When all water loss in a given time period can be attributed to evaporation, then seepage out is nil.

Evaporation from water stored in earth tanks was calculated using Bureau of Meteorology estimates of evaporation (1). A pan to tank coefficient of 0.8 was used (2).

Testing of Trial Tank Sites

Trial excavated tanks were constructed at Badgingarra, Forrestania, and Wongan Hills in soils which were known to offer poor prospects for successful earth tank construction. The following tests were made to determine the suitability of each site:

Five 5-cm diameter auger holes were drilled to 3.5 m depth (approximately 0.5 m deeper than the expected depth of excavation) at each site. One test hole was in the center of the site and one each at the four corners of the floor plan of the tank. The soil from each test hole was sampled at 30-cm intervals, and hand texture tests were recorded for the moistened samples. A limited number of particle size distribution analyses were done also (see tables 2, 3, and 4). From experience of the local situations, it was considered that excavations on these sites would not hold water successfully.

For further confirmation of expected high seepage rates through these soils, rapid estimates were made of water loss rates from the central test hole at each site. The test holes were filled with water of low total salt content (<500 mg/l) and topped up twice daily for 3 days to allow the soil surrounding the hole to approach saturation moisture content. On the fourth day, after topping up, the rate of fall of water level in each hole was monitored.

A test hole to 250 cm in the Wongan Hills site (see table 4) held water for a long period. The water level dropped rapidly to 50 cm, and, within 24 hours, was down to 120 cm; however, after 6 days, the water level was still at 180 cm. This site to 350 cm depth was regarded as quite satisfactory for a successful excavated earth tank. Test holes to deeper levels in this Wongan Hills site lost water much more rapidly. In a hole to 350 cm depth, the water level dropped to 250 cm within 24 hours, and in a hole to 420 cm depth, the water level dropped to 350 cm in 20 minutes.

Test holes in the Badgingarra sites generally showed rapid drop of water level to 200 cm within an hour, and were dry within 48 hours. The Forrestania site was similar to the Wongan Hills site in that water loss rate from a shallow hole (150 cm deep) was relatively slow (water level at 75 cm after 5 hours). In a deeper test hole, to 375 cm, the water level fell to 300 cm within 1.5 hours.

The water loss rate from test holes at all sites was of such magnitude that it was reasonable to expect that excavated tanks on these sites would leak.

Size of Trial Tanks

The trial tanks ranged from 1,000 to 2,000 m^3 capacity, with approximate dimensions as follows:

Depth when full	3.5 m
Surface length and width	32 m
Bottom length and width	9 m
Batter slope ratio	3.5:1

Sealing Techniques and Materials

The following treatment materials were applied to leaking excavated tanks:

Rivaseal--a sheeting composed of a thin polyester film and fiber glass mat laminated together and coated on both sides with a mixture of a selected bitumen and talc. [5]

Polyethylene sheeting--black, 0.20 mm thick.

Bentonite--local (Western Australia).

Sodium tri-polyphosphate (S.T.P.P.).

A summary of costs of treatments is given in table 5.

Rivaseal

Rivaseal was supplied in 27-kg rolls containing sheeting, 11 by 0.9 m. Each roll cost $A9.60 (96¢/m^2).

Two excavated tanks were lined with Rivaseal, one at Forrestania and the other at Badgingarra. The excavation surface was smoothed and rolled to remove any sharp projections and any sudden changes in microrelief. Pisolitic ironstone gravel was particularly troublesome, and required rolling followed by brushing to remove any loose nodules.

An anchor trench was dug 15 cm vertically above the high watermark of the tank. The trench was generally 30 cm wide by 20 cm deep, although across the inlet to the tank it was made deeper.

The sheets of Rivaseal were welded in place in the tank using a portable gas paint burner. The sheets were overlapped 7.5 cm for welding. Every welded seam was checked with a wire probe, and patches were welded over any likely leaks.

On completion of the lining fabrication, the edge of the liner was placed in the anchor trench, which was backfilled with soil. Across the waterway leading into the tank, the backfilled soil was compacted with a vibrating plate to ensure no water would undermine the liner. The lined tank was fenced to exclude animals.

The Rivaseal in both lined excavations was given a maintenance application of a bitumen based aluminum paint after 4 years exposure.

Polyethylene Sheeting

A leaking excavated earth tank at Badgingarra was lined with polyethylene sheeting. The liner was supplied as a prefabricated sheet ready for field installation. It was 0.2 mm thick and black. Individual sheets of polyethylene were joined, prior to delivery, by a heat welding technique. To allow for slack in the liner when installed (to avoid development of undue tension), the liner was 10 percent wider and longer than the longest dimensions along the excavation surface. The prefabricated liner cost $A0.47/m^2.

The liner was installed in the excavation on a 10-cm thick foundation of clean sand, and was covered by a similar thickness of clean loamy sand following Burton's (6) recommendations. The sand foundation was placed with a self-loading rubber-tired scoop, but the blanket of loamy sand on top of the polyethylene sheeting could only be placed by hand. This was a tedious and time-consuming job. The soil cover for the liner was to provide protection against mechanical damage and against the effects of ultraviolet radiation. Due to frequently cloudless skies, the ultraviolet content of radiation in our farming areas is high. [6] Black, polyethylene sheeting (0.15 mm thick) became brittle and was easily damaged after 5 months exposure in this area in summer.

A stable inlet chute was constructed to take runoff water from the catchment safely into the lined excavation. This was necessary to avoid removal of the soil cover on the polyethylene at the point of water entry. An inlet chute was constructed on Rivaseal with edges raised on fence posts wired together, end to end.

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[5] Pabco Products Sales Literature: Stop seepage with Pabco Rivaseal. Pabco Products, Nicholson Road, Canning Vale, Western Australia.

[6] R. H. Sedgley, personal communication.

Other Treatments

The three other treatments (S.T.P.P., bentonite, and cultivation and compaction) all involved some mixing, rolling, and construction of inlet chutes. These thechiques are described below:

Mixing technique.--The surface soil, 15 cm deep in each dam, was ripped with the dozer. The dozer blade was used to push up heaps, which were then back-bladed, thus causing mixing of the soil. This process was continued over the whole excavation surface. The treated soil layer in each case was only 15 cm deep, although the original aim had been to treat 30 cm of soil. (Effective treatment of 30 cm of soil on the excavation batters would require treatment of two 15-cm layers, and this was not possible with the time and equipment available.)

Rolling technique.--Each portion of the excavation surface received at least two passes of a single-drum sheepsfoot roller when the soil was very dry. Further rolling of the dry soil was thought to be useless, and rolling was postponed until rain had thoroughly wet the treated layer. A total of five passes of the sheepsfoot roller were made over all portions of each excavation, with the soil quite moist and plastic. The lower half of each excavation received considerably more rolling than the top half.

Inlet chutes.--A simple inlet chute was constructed for each excavated tank to allow water from the catchment to enter the excavation without eroding the treated layer.

Some shaping of the earth foundation was done with a shovel and rake, to produce a chute about 2 m wide, having a central, lowered area with 20-cm high banks on either side. An anchor trench, 30 cm wide by 20 cm deep, was dug across the top end of each chute.

The earth foundation was covered with Rivaseal, which was anchored at the upper end, and down both sides, with soil. The chutes were extended to the floor of the tank. Each chute required six rolls of Rivaseal and 4 man hours of labor.

Sodium Tri-polyphosphate (S.T.P.P.)

This chemical dispersant has been applied to several excavations at Badgingarra and Wongan Hills. The suitability of these soils for treatment with S.T.P.P. was assessed by reference to the work of Gyarmathy [7] Burton (5), Decker (7), Fonner (8), and Sewell (11, 12) and by laboratory permeability measurements before and after treatment with S.T.P.P.

Various methods of application were tried as follows: (1) Top dress, mix, roll; (2) top dress onto moist soil (when further rain was expected); and (3) top dress onto the water surface.

Methods (2) and (3) did not involve any disturbance of the soil surface, and therefore did not require compaction immediately to stabilize the freshly treated layer of soil.

Rates of application used varied from 0.08 to 0.20 percent (W/W basis in the top 15 cm of soil), depending on the level of chemical required to give a tenfold decrease in laboratory permeability. These rates of application quoted are roughly equivalent to 0.22 and 0.55 kg S.T.P.P./m^2. S.T.P.P. costs approximately $A300/tonne for bulk purchases, and slightly more for small quantities.

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[7] Gyarmathy, A. Senior Research Officer, Soil Conservation Authority, Victoria, personal communication.

When S.T.P.P. application involved mixing the chemical into the soil surface, the disturbed soil layer was rolled, and an inlet chute was provided. When no mixing occurred, an inlet chute was constructed, but no compaction was given. In such cases, a fence was erected to protect the inlet chute, and it was assumed that adequate compaction would result from the trampling of stock watering at the excavated tank. As the water level recedes, all portions of the surface of the tank are compacted.

Bentonite

A local Western Australia bentonite was applied by hand over the surface of the excavation at 5.4 kg/m^2. This product costs $A45/tonne.

The bentonite was mixed into the top 15 cm of soil and rolled, as discussed previously. An inlet chute was provided for safe entry of runoff into the excavation.

Cultivation and Compaction

This treatment consisted of two-way ripping of the excavation surface on a 30-cm grid, mixing of the soil, and rolling, as discussed previously. This treatment was intended to disturb the natural soil structure and to compact the disturbed layer to a medium density.

An inlet chute was provided for safe entry of runoff into the excavation.

RESULTS

The results of the sealing program are presented as water balance studies for each sealed tank in table 7. For excavated tanks of the size range used in this project, the seepage rate corresponding to a water level drop of 600 mm in 200 days, is approximately 6 mm^3/mm^2/day. This assumes the seepage loss, consumption by stock, and evaporation loss are concurrent.

Seepage rates were determined by considering water balance data during periods with no catchment runoff contribution and no consumption of water by stock. For the Rivaseal lined tanks, 100 percent runoff of all falls of rain was assumed for the exposed Rivaseal surface. For the polyethylene lined tank (with a 10-cm soil cover), and for the S.T.P.P., bentonite, and cultivated and compacted tanks, 50 percent runoff of all falls of rain was assumed for the tank batters.

The estimates of evaporation losses from excavated tanks, based on the Bureau of Meteorology estimates (1) multiplied by 0.8 (2), were modified in relation to the departure from the mean of the average daily temperatures (3) for the period.

DISCUSSION

Rivaseal Lined Tanks at Forrestania and Badgingarra

Because unskilled personnel were used to record water levels in the Forrestania tank, the water level changes (and thus the seepage rates) for individual observation periods may be inaccurate. The greatest percentage error would occur when the water level change was small. The overall seepage rate, 4.0 mm^3/mm^2/day, calculated as a weighted average of the results from seven observation periods (see table 7), is regarded as a fair estimate of seepage rate from this tank.

Water level records at Badgingarra were made by technical staff, and individual seepage rate calculations from each observation period are as accurate as is possible considering the assumptions used in field water balance studies. The seepage rate, 4.6 mm^3/mm^2/day (see table 7), corresponds closely to the Forrestania tank seepage rate.

These seepage rates are greater than the best value quoted by Lauritzen and Dedrick (10) for buried prefabricated bituminous sheeting ($<$0.005 ft^3/ft^2/day, that is, 1.52 mm^3/mm^2/day); however, these workers concluded that exposed asphaltic membranes were unserviceable, except for asphalt-jute laminate and coated, asphalt-saturated felt. Their tests were of longer duration than the work reported here. The much greater size of lined storage, depth of stored water, weathering of the exposed liner, and less controlled measurements are all factors that could contribute to the greater seepage rates reported here.

The Rivaseal in both lined tanks showed a marked loss of flexibility after exposure for 4 years. This loss of flexibility was of little consequence where the Rivaseal was on a good foundation, but foot traffic on the liner, where foundations were uneven, led to rapid deterioration of the sheeting. Patching of the Rivaseal was an easy operation; the same heat welding technique was used as in the original installation.

A bitumen-based aluminum paint was applied to both Rivaseal lined excavations after 4 years exposure. This paint should prolong the life of the linter by improving flexibility, increasing reflectivity, and, therefore, decreasing the oxidation rate of the bitumen surface. The aluminum paint cost $A4.40/gal, and approximately $A0.16/$m^2$ of wetted surface (material cost only).

The makers of Rivaseal now recommend that a bitumen-based aluminum paint be applied immediately after the liner is installed.

Polythene Lined Tank

The seepage rate of this tank before lining was 12 mm^3/mm^2/day and after lining with polyethylene was 6.5 mm^3/mm^2/day (see table 7). This result was satisfactory while the polyethylene sheet remained intact.

Less than 9 months after installation, an unusually heavy rainstorm caused a large runoff from the catchment, which caused a break in the collecting channel immediately in front of the lined tank. The lining was undermined by water and soil (including much coarse ironstone gravel). A large fracture in the polythene sheet was patched, but not satisfactorily, and the polyethylene liner is now regarded as useless.

Despite this unlikely occurrence, 0.2-mm polythene is not regarded as a tank lining material with sufficient strength to be practical for application in the West Australian situation. It is too easily damaged. The need to shield polyethylene with a cover of soil puts the cost up considerably, and the total cost then makes the alternative materials a better long-term proposition.

Sodium Tri-Polyphosphate (S.T.P.P.) Treated Tanks

Badgingarra 1

After treatment with S.T.P.P. at 0.1 percent in the top 15 cm of soil in the excavation (including mixing and rolling with a sheepsfoot roller), seepage was 14.2 mm^3/mm^2/day (see table 7).

This estimate was based on the assumption that 50 percent of the rain during the observation period ran off the tank batters. If no rain ran off the batters, the seepage rate estimate would be 10.8 mm^3/mm^2/day; and if 100 percent ran off the batters, 17.5 mm^3/mm^2/day. This result (14.2 mm^3/mm^2/day) is greater than the maximum allowable seepage rate, and the treatment has not reduced seepage rate to an acceptable level.

Badgingarra 2

This tank was assumed to be leaking (from information provided by the owner prior to treatment). The seepage rate measured after treatment with 0.1 percent S.T.P.P. was 6.3 mm^3/mm^2/day. This rate is close to maximum allowable seepage rate, and the excavation is not now regarded as leaking excessively. It cannot be claimed that this tank was sealed with S.T.P.P., but its performance now is satisfactory.

A point of practical significance arose from this particular sealing exercise. The erosion of the treated layer on this excavated tank was extremely severe, due to addition of S.T.P.P. to the soil (and consequent loss of strength), the steep batter slopes (3:1), and the lack of compaction following working of the soil to incorporate the S.T.P.P. On the other occasions when S.T.P.P. has been used, erosion of the treated layer has been much less severe, and this must limit the usefulness of the technique.

Compaction of the treated layer has been referred to by Burton (5) and Fonner (8) as being a necessary adjunct to S.T.P.P. treatment, but on normal 3:1 batter slopes, this calls for specialized equipment. The alternative may be an application of a short-lived stabilizing mulch, such as a dilute bitumen emulsion or a starch derivative mulch.

Wongan 1 and 2

These excavated tanks were shown to have high seepage rates of 120 and 150 $mm^3/mm2$/day prior to treatment with S.T.P.P. (see table 7). Treatment with S.T.P.P. has apparently reduced these high seepage rates to 45 and 85 mm^3/mm^2/day, respectively. The final seepage rates are still far in excess of a tolerable seepage rate, and some other form of tank sealing is probably required in these soils.

Bentonite Treated Tank

The seepage rate of 17 mm^3/mm^2/day (see table 7) calculated for this tank after treatment indicates that this bentonite application has not been successful in restricting seepage rate to a practical level.

Although Burton (4) suggests that bentonite should be used in a mixed-blanket technique on sandy soils only, it was tried as a mixed blanket in this particular case. The pure blanket technique requires considerably more bentonite, and a protective layer of soil, and the costs would then be comparable with the better techniques.

The steep batter slopes and widely fluctuating seasonal water levels in excavated tanks in Western Australia are two factors that may limit the applicability of bentonite for sealing purposes.

Cultivated and Compacted Tank

This tank was shown to have a seepage rate of 12 mm^3/mm^2/day following treatment (see table 7). The treatment was the cheapest of all those tried and may be a useful technique either alone or in conjunction with S.T.P.P. applications. The availability of suitable machinery limits the use of this treatment. It is likely that the disruption of the natural soil structure with this treatment may be a factor in seepage rate reduction. The seepage rate of 12 mm^3/mm^2/day is still too high to be regarded as an acceptable loss rate.

CONCLUSIONS

From the results of water balance studies, and from experience gained in installation of the sealing techniques applied, the laminated sheeting (Rivaseal) appears to offer best prospects for seepage control in leaking excavated earth tanks on farms in Western Australia.

Rivaseal is robust and readily available and can be installed with unskilled labor, used as an exposed liner, walked on by humans, and readily patched. The price of a Rivaseal lining (see table 5) is far more than can be justified if an alternative site for an excavation exists (see table 1). Where no alternative exists, or where the alternative is to develop an underground water supply, then a Rivaseal lining may be economically feasible for a stock water supply.

The asphalt-fiberglass linings, reported by Frasier, Myers, and Griggs (9), are economically more attractive than Rivaseal and have similar features to Rivaseal as previously listed. The field installation of the asphalt-fiberglass linings appears to be more complicated than the simple welding required for Rivaseal.

Polyethylene sheeting was tried, but is regarded as too easily damaged and too difficult to patch once a soil cover has been applied. Also, the required soil cover poses many problems, such as the actual placement of the soil cover, the stability of the cover, and damage resulting from birds, which dig through the soil cover and then peck holes in the polyethylene film.

S.T.P.P. has been tried on several Western Australia soils. In the laboratory, hydraulic conductivity of Badgingarra and Wongan Hills soils have been decreased following S.T.P.P. treatment. In the field, seepage rates have been decreased in Wongan Hills soils, but after treatment with S.T.P.P., the seepage rates were still higher than an acceptable value. There is no evidence that seepage rate reduction has resulted from the use of S.T.P.P. on Badgingarra soils.

S.T.P.P. provides a cheap treatment, which would find wide use if recommended. The problems associated with erosion of the treated soil layer will have to be solved before the technique can be universally acceptable.

The other treatments tried were application of a local bentonite and cultivation and compaction. Under some conditions, these techniques may prove useful in conjunction with other treatments. Alone, these treatments are not likely to lead to successful sealing of excavations.

ACKNOWLEDGMENTS

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Thanks are also due K. Taylor and R. Davison of Badgingarra for the opportunity to work on their leaking excavated tanks.

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APPENDIX

TABLE 1.--Variation of wetted surface (or surface requiring sealing) with increasing tank capacity for prismoidal shaped excavated earth tanks having uniform batter slopes of 3:1

Tank capacity	Depth of tank	Wetted surface	Wetted surface per cubic meter capacity	Maximum sealing cost 1/ per square meter
M 3/	M	M^2	M^2/m^3	$\$A/m^2$
770	3.05	557	0.72	0.41
1,540	3.35	898	.58	.51
2,310	3.66	1,186	.51	.58
3,080	3.96	1,440	.47	.64
3,850	4.58	1,652	.43	.70
4.620	4.88	1,865	.40	.74

1/ Maximum allowable sealing treatment cost where an alternative tank site exists. That is, the alternative to sealing the leaking tank is to construct a similar sized tank on a new site. The cost of the replacement tank was calculated at $\$A0.30/m^3$.

TABLE 2.--Soil profile, soil textures, and particle size analyses for an excavated tank site at Badgingarra

Depth (cm)	Field description and soil texture	Clay 1/ <0.002 mm	Silt 0.002 - 0.02 mm	Fine sand 0.02 - 0.2 mm	Coarse sand 0.2 - 2.0 mm	Gravel 2/ >2.0 mm	Dispersion 3/
		Percent	Percent	Percent	Percent	Percent	
0-30	Gray, very gravelly sand (much coarse ironstone nodules).	2	0	37	61	35	Nil
30-60	Pale yellow-brown, gravelly, loamy sand.	4	1	40	55	25	Nil
60-90	Yellow and red-brown, mottled, sandy clay loam.	17	6	35	42	0	Nil
90-350+	Off-white and yellow with red-brown mottled, light, sandy clay.	25	5	32	38	0	Slight

1/ Kaolinite dominant.

2/ Ironstone pisolitic gravel.

3/ Crumb dispersion tests in distilled water.

TABLE 3.--Soil profile, soil textures, and particle size analyses for the excavated tank site at Forrestania

Depth (cm)	Field description and soil texture	Clay 1/ <0.002 mm	Silt 0.002 - 0.02 mm	Fine sand 0.02 - 0.2 mm	Coarse sand 0.2 - 2.0 mm	Gravel 2/ >2.0 mm	Dispersion 3/
		Percent	Percent	Percent	Percent	Percent	
10-60	Yellow, loamy sand	16	3	15	66	0	Nil
60-180	Bright-yellow, sandy clay loam.	21	2	36	41	0	Nil
180-330	Yellow and red-brown, sandy clay loam.	24	0	33	43	1	Nil
330+	Yellow and gray gravelly, sandy clay loam.	11	0	39	50	8	Slight

1/ Kaolinite dominant.

2/ Ironstone pisolitic gravel.

3/ Crumb dispersion tests in distilled water.

TABLE 4.--Soil profile, soil textures, and particle size analyses for an excavated tank site at Wongan Hills

Depth (cm)	Field description and soil texture	Clay 1/ <0.002 mm	Silt 0.002-0.02 mm	Fine sand 0.02-0.2 mm	Coarse sand 0.2-2.0 mm	Gravel 2/ >2.0 mm	Dispersion 3/
		Percent	Percent	Percent	Percent	Percent	
0-60	Orange-brown, sandy clay.	42	3.5	13.5	41	0	Slight
60-250	Yellow and red-brown tough, sandy clay.	55	9	11	25	0	Nil
250-280	Pale-gray, sandy clay.	39	20	9	32	1.5	Slight
280-450+	White, sandy clay loam.	18	31	12	39	1.5	Nil

1/ Kaolinite dominant.

2/ Angular quartz.

3/ Crumb dispersion tests in distilled water.

TABLE 5.--Comparative costs of sealing treatments for small (1,000 to 2,000 m^3) excavated earth tanks in Western Australia, 1973

Treatment	Sealing materials	Mixing and/or compaction	Inlet chute	Labor, incidentals, and other expenses	Fencing	Total treatment
	$\$A/m^2$	$\$A/m^2$	$\$A/m^2$	$\$A/m^2$	$\$A/m^2$	$\$A/m^2$
Rivaseal	1.20	0.10	0	0.80	0.10	2.20
Polyethene 0.2 mm	.47	.08	.12	1/.70	.10	1.47
Polyethene 0.3 mm	.70					1.70
S.T.P.P. 0.1%	.08	.15	.10	.10	2/.02	.45
S.T.P.P. 0.2%	.17					.54
Bentonite	.24	.15	.10	.10	2/.02	.61
Cultivation and compaction	0	.15	.10	.05	2/.02	.32

1/ Includes labor and supply and placing of sand foundation and cover.

2/ Fencing of inlet chute only.

TABLE 6.--Comparison of laboratory hydraulic conductivity 1/ of soils before and after treatment with sodium tri-polyphosphate (S.T.P.P.)

Soil and sequence of permeating solutions	Mean hydraulic conductivity
	Mm/day
Badgingarra (No. 1) Light Sandy Clay:	
Tapwater	50
0.22% S.T.P.P. solution 2/	5
Tapwater	3.5
Wongan (No. 2) Sandy Clay Loam:	
Tapwater	17
0.24% S.T.P.P. solution 2/	3
Tapwater	2.2
0.48% S.T.P.P. solution	1.7
Tapwater	1.7

1/ Method Used: 100 g of air dry soil (passing a 2-mm sieve) was dry tamped (25 blows on bench top) on top of 50 g of clean washed quartz sand in a simple Plexiglas permeameter of 8.9-cm internal diameter. Hydraulic head was maintained at 10 cm, and temperatures were kept constant at 18° C. Mercuric chloride was added to the solutions to prohibit growth of organisms during the measurements. Tapwater water containing 400 ml/l total soluble salts was used for basal permeability measurement. The permeameters was replicated 4 times.

2/ = 0.1% S.T.P.P. in soil, W/W dry basis.

TABLE 7.--Water balance data

Type of tank and observation period	Water levels in tank Start	Water levels in tank Finish	Rainfall	Estimated evaporation from tank	Estimated seepage	Seepage rate
	Mm	Mm	Mm	Mm	Mm	Mm3/mm2/day
Rivaseal-lined tank at Forrestania:						
Mar. 2 - 30, 1970	2,591	2,362	1	174	+ 55	+ 5.4
Dec. 6, 1970 - Jan 1, 1971	2,743	2,591	9	172	- 6	- .6
Jan. 1 - Mar. 1, 1971	2,591	2,134	20	450	+ 36	+ 1.6
Apr. 10 - June 27, 1971	2,865	2,621	35	156	+128	+ 4.5
Oct. 30 - Dec. 5, 1971	2,819	2,652	33	196	+ 12	+ .8
Dec. 5, 1971 - Jan. 4, 1972	2,652	2,362	5	183	+113	+10.3
Jan. 4 - Mar. 4, 1972	2,362	1,829	18	440	+122	+ 5.0
Total					+460	
Mean						+ 4.0
Rivaseal-lined tank at Badgingara:						
Aug. 19 - Sept. 9, 1968	1,101	1,134	32	49	+ 35	+ 3.3
Sept. 16 - Oct. 21, 1968	1,256	1,189	44	122	+ 91	+ 5.2
Sept. 10 - Dec. 15, 1970	1,465	975	67	470	+219	+ 4.6
Mean						+ 4.6
Polythene-lined tank:						
Sept. 10 - Dec. 15, 1970	3.270	2,655	66	472	1/+216	+ 6.5
Sodium tri-polyphosphate treated tanks at Badgingarra 1:						
Aug. 19 - Oct. 28, 1968	1,618	1,205	128	222	1/+ 40	+14.2
Sodium tri-polyphosphate treated tanks at Badgingarra 2:						
Aug. 5 - Sept. 9, 1969	1.400	1,312	25	61	1/+ 77	+ 4.5
Sept. 9 - 30, 1969	1,312	1,245	7	76	1/+ 3	+ .3
Sept. 10 - Dec. 15, 1969	1,922	1,160	66	472	1/+356	+ 8.2
Mean						+ 6.3
Sodium tri-polyphosphate treated tanks at Wongan 1:						
Before treatment--						
Feb. 16 - 19, 1970	1,222	1,000	0	24	+198	+ 120
After treatment--						
Feb. 19 - Mar. 12, 1970	1.000	256	0	94	+650	+ 45

See footnote at end of table.

TABLE 7.--Water balance data--Continued

Type of tank and observation period	Water levels in tank		Rainfall	Estimated evaporation from tank	Estimated seepage	Seepage rate
	Start	Finish				
	Mm	Mm	Mm	Mm	Mm	Mm^3/mm^2/day
Sodium tri-polyphosphate treated tanks at Wongan 2:						
Before treatment--Feb. 16 - 19, 1970	2,130	1,916	0	24	+ 190	+ 150
After treatment with 0.1 percent S.T.P.P.--July 1 - 14, 1970	1,482	915	0	18	+ 550	+ 85
Bentonite treated tank:						
Sept. 20 - Oct. 20, 1968	731	381	41.5	106	1/+ 355	+ 17
Cultivated and compacted tank:						
Sept. 20 - Oct. 20, 1968	290	15	41.5	106	1/+ 340	+ 12

1/ Assuming 50 percent of all rain falling on batters of tank ran into storage.

STORAGE SYSTEMS FOR HARVESTED WATER

A. R. Dedrick [1]

INTRODUCTION

A storage facility is generally required for most water-distribution supply systems. In many instances, the distribution part of the system can be more economically designed if a storage facility is provided, as in the case of water accumulating from a small conveyance system used only intermittently. In addition, where water supplies are limited and intermittent use rates exceed the rate of supply, storage is essential for proper system operation, as in low yield springs, wells dependent on windmill operation, and water harvesting catchments dependent on highly variable, nonuniform precipitation.

Water storage, as discussed here, will be directed primarily toward water harvesting systems but may be applied to any other water sources. The storage facility may also be associated with various water supply uses, including livestock, wildlife, and domestic and supplemental water for agricultural crops. Selection of the system used would many times be dictated by the intended use of the water.

Requirements of the water storage system, general storage considerations, and various modes of water storage will be discussed. Specific materials used to produce efficient water storage systems for the various modes will be considered. No recommendations will be made for the best mode or material, since the one eventually used will be dependent upon local conditions such as:

1. Soils (chemical and physical properties).
2. Accessibility regarding personnel, equipment, and materials.
3. Availability of various materials.
4. Costs at that particular time and place.
5. System life requirement.

The designer should keep in mind that the best storage system for a given location is the one that produces water at the lowest unit cost.

STORAGE SYSTEM REQUIREMENTS

Storage requirements must be balanced against the quantity of precipitation for the area and the associated reliability of receiving this precipitation. Capacity generally increases as requirements increase and as amounts available decrease and become less reliable.

Storage requirements can usually be closely estimated by considering the purpose for which the water is to be used, use periods, and the water requirement of the intended use unit (livestock, game population, household members, and so forth). Determination of supply is more difficult, especially when dependability or probability of having water is taken into account. The probability level should be high enough to satisfy the requirements of the system but not so high that the system is is greatly overdesigned (30). The refinement with which the analysis is done depends on precipitation records for the site in question. Insufficient precipitation information will dictate an estimate of the precipitation using nearby gaging stations or other means, such as vegetative indicators, that are responsive to precipitation. These indicators, however, can be masked by other factors and must be applied with caution.

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The potential quantity of water developed from a water harvesting system is in proportion to catchment area. Cost of water developed, aside from material costs, is dependent upon proper sizing of the system and its efficiency. The quantity of water available per unit area for a certain reliability level is fixed for a given site, but the efficiency with which it is collected and stored may be variable. Depending on cost structure, there is a level of inefficiency that can be tolerated, but above which it is advantageous to limit further inefficiencies.

To illustrate cost considerations, if the storage part of a water harvesting system does not approach 100 percent efficiency, an example will be given using basic system sizing design information from Ree et al. (30). In this example, Ree et al. assumed that the use rate was 200 gal/day (13 to 15 head of cattle) on a year-round basis and that 99 percent probability of having water was acceptable. One combination of catchment and storage that would accommodate these requirements was 7,000 ft^2 for the catchment area and 16,700 gal for the storage. Other catchment-storage combinations are acceptable, but for illustrative purposes that one will be used. These figures, for Stillwater, Okla., assume 100 percent storage and catchment efficiency.

Assume now a system similar to that shown in figure 1, in which a

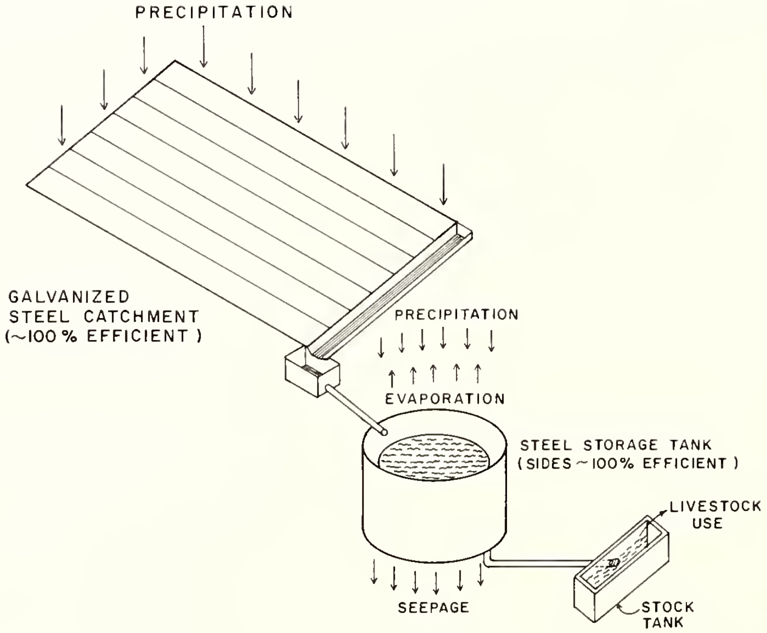
PRECIPITATION
GALVANIZED STEEL CATCHMENT (~100 % EFFICIENT)
PRECIPITATION
EVAPORATION
STEEL STORAGE TANK (SIDES ~ 100% EFFICIENT)
LIVESTOCK USE
SEEPAGE
STOCK TANK

FIGURE 1.--Diagram of water harvesting system used in analysing the effect that water losses from storage have on catchment area, storage requirements, and the related initial cost of the total system.

galvanized steel catchment--essentially 100 percent efficient (22)--is used in conjunction with a steel tank (sidewalls watertight). Water losses from the tank may occur by both seepage and evaporation, whereas water gains may occur from precipitation collected on the catchment and in the tank. The water balance for the system is $C_h = C_e + C_s + C_u + C_o$, where C_h is water harvested, C_e is evaporation rate, C_s is seepage rate, C_u is livestock use rate, and C_o is miscellaneous losses. For discussion purposes, evaporation and seepage losses will be combined with other losses into one loss rate term, $C_\ell = C_e + C_s + C_s + C_o$. The equation describing water balance then becomes $C_h = C_\ell + C_u$.

The effect that losses have on designing for probable C_h, in terms of increased catchment area and storage requirements, is illustrated in figure 2. The sizing combinations were again taken from Ree's analysis.

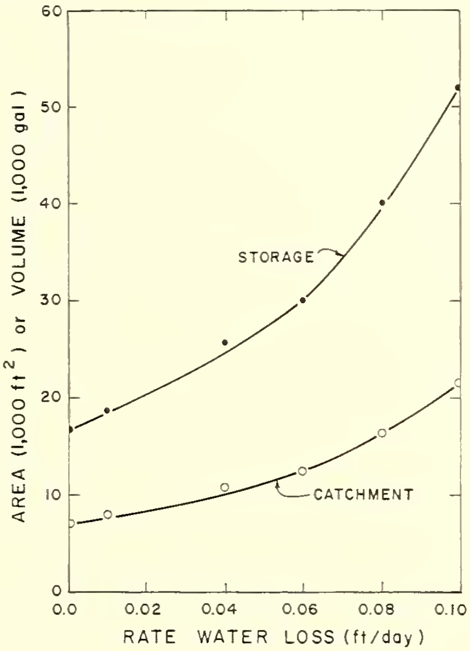

FIGURE 2.--Required catchment area and water storage volume related to storage losses for system illustrated in figure 1. Precipitation patterns used in the development of the curves were for Stillwater, Okla., for a reliability level of 99 percent.

Area and volume requirements nearly tripled when system losses (C_ℓ) increased from zero to 0.1 ft/day.

These requirements were next converted into initial costs using the following equations:

1. Cost of galvanized steel catchment (C_c) in dollars per 1,000 $ft^2 = 390/A_c^{0.21}$ for A_c less than 4 or $300 - 3 A_c$ for A_c greater than 4 where A_c is area of catchment in thousands of square feet.

2. Cost of galvanized steel grain bin sidewalls (C_w) in dollars per 1,000 gal = $90/V^{0.46}$, where V is thousands of gallons stored.

Total initial cost (C_t) for the subject water harvesting system for water losses up to 0.1 ft/day is shown in figure 3. The cost curve is of the form $C_t = a(10)^{bC_\ell}$, which indicates a logarithmic increase in cost

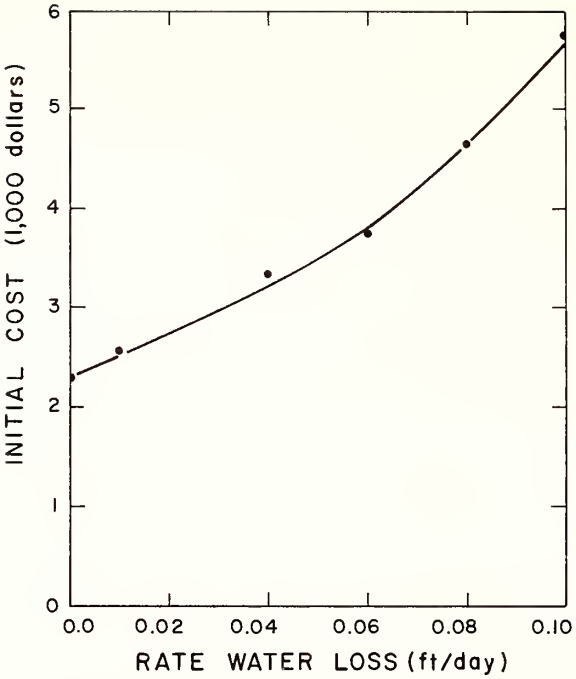

FIGURE 3.--Initial cost of water harvesting system related to storage losses for the system illustrated in figure 1.

with linear increases in water loss. Extrapolation of such relation beyond the limits illustrated would soon yield astronomical initial system costs. For the example given (a = 2,300, b = 3.93), if the water loss rate were 0.5 ft/day, the initial cost would be nearly a quarter of a million dollars ($214,000) to supply year-round water for only 13 to 15 head of cattle.

To offset the extreme costliness of water storage losses, means of storing water efficiently must be considered. The galvanized steel grain bin shown in figure 1, for instance, could be made nearly watertight by lining it with plastic (10) to control seepage and floating a foam rubber cover (9) to control evaporation. The added costs of these features (prices, as of January 1974, include material cost, labor, and excavation) raise the initial cost of the system from $2,280 to $3,550, whereby inspection of figure 3 shows that any time water losses are greater than about 0.053 ft/day (corresponding to initial cost of $3,550), it is economical to impose this means of water loss control on the system. If the seepage and evaporation could be controlled more economically, the allowable loss level would correspondingly decrease.

Evaporation losses in some areas of Southwestern United States average one-third this rate year round and two-thirds during summer months (6). The average annual evaporation rate at Stillwater is approximately 5 ft/yr or 0.0137 ft/day (34), approximately one-fourth the allowable rate for the conditions of the example. Hence, seepage losses should not exceed the difference between 0.053 ft/day and the evaporation rate for the area, and can be referred to as the level of inefficiency that can be tolerated for this particular situation. In most areas, soil conditions are such that seepage losses would far exceed the tolerable limit and must be controlled.

GENERAL STORAGE CONSIDERATIONS

To minimize seepage and evaporation losses, storage structure volume should be maximized and containment and exposed surface area should be minimized. The ratios of volume stored to containment or water surface area increases as the depth of the storage increases in relation to its breadth. Excavated storage pits associated with water harvesting systems generally have depth-to-breadth ratios ranging from 1/5 to 1/15 (8 and Wisdom, D. F., written commun., 1972). Advantages could be achieved if storage systems were constructed deeper.

The respective ratios of volume stored to containment or water surface area also increase as the sideslope of the pit steepens. A storage structure with vertical walls is superior to one with sloping sides; however, there are equipment and soil stability limiations in the excavation of pits and ponds. Also, the depth of a water storage structure is limited by the need to maintain a gravity inflow-outflow setup. Some of these limitations can be overcome by using constructed sidewall tanks.

DESIRABLE WATER BARRIER CHARACTERISTICS

When considering a lining material for a water storage structure, certain features should be evaluated as follows:

1. Degree of seepage control that can be expected. Ideally, the water barrier would be watertight, but from an economic standpoint this may not be attainable.

2. Resistance to deterioration by soil microorganisms, atmospheric elements (heat, ozone, oxygen, sunlight), wind, and subgrade movement.

3. Mechanical puncture and vermin attack.

4. Toxicity.

5. Ease of installation.

6. Transportability with respect to the use site.

7. Maintenance requirements.

8. Economy.

This list should be used as a guide in selecting a lining material for a given set of conditions. In some instances, an apparent disadvantage in one category may not be serious, depending on the specific requirements of the storage structure and pond site.

EXCAVATED PITS OR PONDS

Excavated pits or small ponds are easily constructed in relatively flat areas with deep soils; and their general compactness has led to wide use. In many instances, the excavated pit must be made watertight by means of a lining material. The type of material used may vary with the site of the pit, success or failure being the result of subgrade materials. Many times, the soil mantel is very thin, and excavation exposes highly permeable and coarse textured subgrade materials.

A spillway or overflow must be part of the excavated pit design, and it must be stabilized to resist eroding effect of the water. Lined drainage channels and closed conveyance systems may be used for this purpose.

Some means of controlling erosion of the lining material itself (or cover material for buried lining) should be considered. A topping of coarse material may do the job. If the water level is variable, the cover should extend over the entire slope; whereas, protection can be limited to an area corresponding to an expected constant water level.

Generally, if an excavated pit or pond is located so that watering troughs can be fed by gravity flow, it is necessary to fence the area, as most lining materials may be physically damaged by livestock trampling. Fencing also helps to protect the spillway and overflow system. In a few cases, reservoir trampling is beneficial for sealing new reservoirs that are lined with various earth materials.

EARTH LININGS AND CHEMICAL TREATMENTS

Seepage control attainable with these types of lining materials is highly variable. In certain instances, they can be used with water harvesting systems, since a relatively high degree of water seepage control can be attained if the site conditions are right. The resultant seepage control may be adequate, depending mainly on the precipitation for the area and the price structure of the catchment materials.

Compacted Earth

Suitable materials, often available near the pond site, may be used to construct a thick, compacted earth lining. Gravelly and sandy clays, with plastic indexes ranging from 12 to 24, are best suited for thick, compacted earth linings (25, 38). Soils with too much clay--higher plastic indexes--are sticky and difficult to handle, whereas soils with too low a plastic index are susceptible to frost damage. Linings of this type are placed in layers and compacted at near optimum moisture to attain maximum compaction. Such an operation necessitates the use of compaction equipment and requires water at the site. Thickness is dependent on depth of water to be stored, but should not be less than 8 inches (36). Livestock should be fenced from this type of lined pond.

Bentonite

Sodium bentonite, a fine-textured oolloidal clay, has been used successfully to reduce seepage in soils containing high percentages of coarse-textured particles (13, 32). When bentonite is wet it absorbs several times its own weight of water and when saturated swells from 8 to 20 times it original volume (37). A good sealing bentonite must have a sufficient amount of exchangeable sodium to disperse the clay particles. Deterioration of a bentonite lining may occur if stored water is high in exchangeable calcium or magnesium--sodium displaced by other cations.

Bentonite has been successfully used as a layer of blended soil-bentonite covered with a layer of fine- to medium-textured soil (32), and also by incorporation of the required amount into the surface soil to a depth of 6 inches as recommended by the Soil Conservation Service (SCS) (36). If left without a protective cover, the lining may crack if allowed to dry, yielding an unsatisfactory lining. Application rates generally range from 1 to 3 lb/ft^2. A laboratory analysis, similar to that of Dirmeyer (12), is recommended as a guide in classifying the bentonite to be used and determining application rate. In certain instances, trampling by livestock has been helpful in working the bentonite into the soil, but fencing after a period of time is generally advisable.

Chemical Additives

Many soils are highly aggregated and porous, resulting in ineffective water storage ponds. By addition of various chemicals, these aggregated soils can be dispersed, resulting in reduced permeability. Various types of soluble salts have been evaluated as soil dispersants. In a laboratory study by Agey and Andrew (1), 74 different soluble salts were evaluated. Sodium salts decreased seepage rates by several hundredfold. Sodium carbonate was the most effective when treatment costs and ability to reduce seepage were considered. Sodium chloride and various types of sodium phosphates were also found to be effective seepage controls. The SCS (37) recommends the use of tetrasodium pyrophosphate and sodium tripolyphosphate as well as sodium chloride and sodium carbonate. However, in studies in Arizona (31), sodium chloride failed within 6 months in a treated stock tank and the sodium phosphates failed in 18 months in field trials. Sodium carbonate was found to be superior over a long period of time in field studies, reducing seepage from as much as 5 inch/day to 0.15 inch/day. Reginato et al. (31) listed three criteria for applying sodium carbonate to attain effectiveness: (1) Depth of soil overlying sand, gravel, or porous rock should be at least 12 inches; (2) clay content of soil should be at least 15 percent; and (3) cation exchange capacity (CEC) should exceed 15 milliequivalents per gram of soil.

The SCS (37) recommends application rates of sodium carbonate of 0.1 to 0.2 lb/ft^2. Reginato et al. (31) presented an equation for calculating the amount of sodium carbonate required for treatment. Retreatment every 2 or 3 years may be necessary to assure continued seepage control. The Arizona work was done without soil compaction or fencing. Others (7, 37) recommend compaction, and to maintain compaction, fencing is required.

Chemical Sealants

Several chemicals, other than salts for sealing soils, have been tried with varying degrees of success. They include waxes, asphalt, resins, and polymers, generally in the form of emulsions. Chemical sealants, when applied to the soil, react chemically to form (1) semisolid or solid gels, (2) deposit precipitates in the soil voids, or (3) otherwise render the subgrade impervious to water. It is desirable to have them filter into the soil, but stop within 6 to 12 inches of the surface. Success in maintaining a satisfactory seal, for use in conjunction with storage systems similar to those used for harvested water, has not been predictable, therefore, the various materials will not be discussed here.

Membrane and Film

Membrane and film materials can be either exposed or buried. If a material will retain its watertightness when exposed to weathering processes and is not easily damaged mechanically, then its use as an exposed liner may be possible. Exposed linings are desirable because sideslopes into the excavated pit can be steeper than if buried linings are used. The ratio of vertical to horizontal sideslopes for excavated pits may be 1:2 or steeper depending on the soil (2). In no instance should the slope exceed the angle of repose of the embankment material. Sideslopes on which buried membrane or film linings are used generally should not exceed 1:3. The steepness would depend to a certain extent on on the type of soil cover and the membrane or film used.

When a buried membrane is to be used for seepage control, the earth structure should be over-excavated to accommodate the cover material. The subgrade should be cleared of all sharp objects that might puncture the liner. If the subgrade is coarse textured to the extent that the water barrier could be punctured, a fine-textured cushion should be laid in the pit before installing the liner (19). Recommended cover thickness varies from 6 inches (2) to 12 inches (19) with the layer next to the liner not coarser than silty sand. The top layer should be gravel.

The amount of cover is mainly dependent on what protection is required from various sorts of mechanical damage.

Many of the flexible membrane and film materials are susceptible to plant puncturing. Thus, as a general practice, a soil sterilant should be applied to the subgrade prior to liner installation. The cover soil used for a buried liner will develop some plant growth. Certain buried asphaltic membrane materials have been punctured by alfalfa roots but butyl rubber was not (17). An extensive examination of a buried plastic canal lining--after 10 years of service in the Delta, Utah, area--showed no saltgrass root penetration. The roots matted between the plastic and soil cover material--an apparent low growth resistance area. This condition existed both above and below the normal waterline.

All flexible membrane lining materials should be anchored in a trench around the perimeter of the pit at the top of the sideslope. The anchor trench cross section should be about 12 inches wide and 8 to 12 inches deep, depending on the size of the pond.

Some commonly used membrane and film liner materials will now be briefly discussed. Physical property specifications, detail installation recommendations, and maintenance requirements can be found in various publications (2, 35, 36, 38).

Prefabricated Asphaltic Plank

Prefabricated asphalt lining materials consist of some form of asphalt applied to various reinforcing materials such as kraft paper, glass fiber mat, asbestos felt, and asbestos fiber. One of the more successful planking materials reported by Lauritzen and Dedrick (23) was commercially produced from catalytically blown asphalt reinforced with asbestos fiber. The liner was most effective when buried. Another satisfactory prefabricated liner was a sandwich type, consisting of an asphalt-saturated felt with outer seal coats on both sides. This same type liner has controlled seepage from a small test pond in Logan, Utah, since 1960. The liner has been used exposed. Joints are sealed with an asphaltic mastic. When used as an exposed liner, the surface should be coated above the waterline every 3 or 4 years with an aluminized paint to retard degradation. Occasional recaulking of some of the joints may be required. Use of unskilled labor and minimal equipment requirements are advantages of this type of lining. Attaining watertight joints is difficult with this material.

Hot Applied Asphaltic Membrane

This lining consists of a membrane of high-softening-point asphalt sprayed in place at high temperatures (400° F). These liners have maintained a high level of seepage control (15, 38), but have the disadvantage of needing special equipment for installation. The membrane should be used only as a buried membrane. Expected effective life for the plank and membrane is unknown, but when buried was effective for 18 years (23).

Reinforced Asphaltic Membrane

This lining material consists of a substrate matting of fiber glass or polypropylene generally made watertight by using asphalt--either emulsion or cutback. Linings are fabricated in the field to the shape of the excavated pit or pond. Liners generally can be used exposed.

Installation procedure and material requirement for asphalt fiber glass linings was described by Frasier et al. (14). Briefly, the process involves shaping the subgrade, spraying the soil at a rate of 1/4 gal/yd^2, unrolling the fiber glass matting (3/4 to 1 oz/ft^2) on the soil surface, spraying or brooming the surface with 1/2 to 3/4 gal/yd^2, and applying a seal coat of asphalt-clay roof type emulsion at a rate of 1/2 gal/yd^2. One seal coat is generally recommended for pond depths up to 10 ft. New seal coats will need to be applied periodically with frequency dependent upon quality of material used, care of application, and severity of weathering forces. Joints are made by overlapping the matting about 4 inches.

Pressure cell tests have shown the described liner to be useful for hydraulic heads up to 10 ft. Some problems have been encountered in maintaining watertight joints; however, if care is taken during the construction of the liner, adequate joints are possible. The liner is quite resistant to mechanical damage due to puncturing.

A polypropylene fiber mat hydraulically sealed with an asphalt-emulsion-asbestos mixture has been developed and is available commercially (4). The fabric is supplied in roll widths of 15 ft. Sheets are cut to fit the pit and sewn in place using an industrial sewing machine driven with compressed air. The sealant used is anionic asphalt emulsion filled with asbestos fibers. Asbestos fibers improve weatherability, elevate softening point, and increase resistance to flow under hydraulic head. The asphalt-asbestos water mixture is applied to the matting in two equal coats of 0.7 gal/yd^2. Overnight cure of the first coat is generally adequate. Sealant can be sprayed or brushed on the surface. Crushed rock is generally used to provide an abrasion-resistant surface with the added benefit of serving as a ballast against wind lift.

During 2 years of study, no measurable seepage losses have been recorded from test channels lined with polypropylene fiber lining at Logan. Hydraulic head in the channels is only 1 ft, but pressure plate tests at the U.S. Water Conservation Laboratory at Phoenix, Ariz., have shown the liner to withstand air pressures to more than 30 psi at 75° F. Maintenance requirements are unknown at this time, but additional asphaltic coatings could be applied if necessary. The membrane could be damaged by sharp objects; hence, fencing is a necessity. Pit sideslopes should not be steeper than 1:2 for either fiber glass or polypropylene-reinforced liners. Soil sterilants should be used for both liners discussed.

Plastic Film

Standard (Buried and Exposed) Film

Several types of plastic film have been used as seepage barriers. Success has been limited mainly to their use when buried, since most plastics degrade when exposed to sunlight and are susceptible to mechanical damage. Polyvinyl chloride (PVC), polyethylene (PE), and chlorinated polyethylene (CPE) have been used most. Various properties of the three plastic films were discussed in detail by Moeller and Ryffel (26).

Film thickness for buried film should be 8 to 10 mils (1 mil = 0.001 inch) depending on the subgrade soil (2). The films are not strong structurally but are highly impermeable. Hence, with proper subgrade preparation the watertightness can be maintained. PVC and CPE are more flexible than PE and hence can be handled more easily at a wider range of temperatures. PVC and CPE also have the advantage of being solvent weldable for seaming and patching purposes. PVC is also more resistant to mechanical damage by puncturing. PE film is the least expensive of the three. Some of the inherent disadvantages in the use of PE can be overcome by handling and installing the material properly. PE can be seamed by heat sealing, tapes, or adhesives. Overlaps of 12 to 18 inches with a caulking strip between sheets creates a watertight joint once the cover material is in place. PVC and CPE should be laid on the subgrade in a relaxed state or with slight slack, whereas PE should have approximately 5 percent slack. Lining materials should not be placed when the temperature is below 32° F or above 100°, since susceptibility to damage during installation increases at temperatures outside this range.

PVC and CPE have been used in a few exposed lining situations with varying and unpredictable success. All of the lining materials depend on carbon black additives or other ultraviolet absorbing chemicals to reduce damage from direct sunlight. Weatherability of PVC is dependent to a considerable degree on type of plasticizer used. The presence of chlorine in a film such as CPE helps to reduce ultraviolet degradation.

Buried plastic linings, installed in test reservoirs in 1954 at Logan, have controlled seepage to date (21 years). The plastic was examined after 17 years. PVC had stiffened--plasticizer loss--but physical properties of PE met new plastic specifications. However, if PVC were undistrubed, watertightness would continue, and such has been the case since inspection.

Plastic-lined, Rock-filled Ponds

Plastic-lined, rock-filled excavated pits are a variation of the standard, buried, plastic-lined pond with the main difference being that the pond is completely filled with rock rather than just covered with earth to protect the plastic. Cluff (5) has evaluated one such installation at an experimental test site and two under field conditions.

Two or three layers of 10-mil PE film are used to line the pit, the surface of which has been prepared similarly to that described for all excavated pits. The plastic is then covered with a layer of used tires filled with fine-textured soil. Rocks, greater than 1 1/4 inches in diameter, are then used to fill the pond. The main function of the tires is to absorb the shock of filling the pit with rock. An inexpensive supply of rock is essential for such an installation.

Freedom from vandalism and reduction of evaporation losses by as much as 90 percent are advantages of the rock-filled pits over open storage systems. Reduced storage space due to the rocks requires that the size of the excavated pit must be increased, which will increase the amount of materials needed per unit volume of water stored. Susceptibility to damage during the rock-filling operation and the need for an easily accessible supply of rock and associated equipment necessary for obtaining rock are disadvantages of the system.

Synthetic Rubber

A number of synthetic rubber membrane materials are currently used as water barriers. They include butyl rubber, ethylene propylene diene monomer (EPDM), and chlorosulfonated polyethylene. Butyl has been used as a water barrier since 1947 (24). EPDM is being used more as time goes on, first making inroads into the water barrier field after 1963. Chlorosulfonated polyethylene has been used more recently, mainly when the liner comes into contact with hydrocarbons.

All synthetic rubber sheetings can be used as exposed lining materials, but must be adequately protected against mechanical damage and are subject to damage due to vandalism and burrowing animals. Inherently, synthetic rubber membranes are resistant to many weathering processes that cause failure in other membrane and film materials. Butyl rubber is, however, susceptible to damage by atmospheric ozone in conjunction with relatively high temperatures and stretching of the membrane. EPDM and chlorosulfonated polyethylene are more ozone-resistant rubbers and hence may be expected to weather better than butyl.

Rubber membranes are manufactured in roll widths ranging from 48 to 72 inches. Large sheets can be factory fabricated for delivery to the field. Sheet size is only limited by handling weight. In the field, membranes can be spliced and patched by use of contact adhesives and, in some instances, uncured rubber. Bonding of EPDM is somewhat more difficult than butyl, whereas chlorosulfonated polyethylene appears to have a splicing advantage.

Materials can be fabricated in numerous thicknesses, the most common being 1/32-, 3/64-, 1/16-, 3/32-, and 1/8-inch. They can also be obtained with or without fabric reinforcement. Nylon has been the most popular reinforcing material used. For most excavated pit linings associated with water harvesting systems, 1/32-inch nylon-supported liners are adequate.

Reservoir sideslopes should be no steeper than 1:2, as long as the angle of repose of the soil is not exceeded; however, reinforcing material must be used to reduce stressing of the rubber at the anchor trench around the perimeter of the pit. Lesser slopes will reduce the possibility of damage to the membrane.

Detailed information regarding laboratory evaluations, field installations, recommendations for use, and physical property requirements are found in several publications (2, 16, 21). These should be consulted for more information. Most manufacturers and distributors supply recommendations for use of their materials. These should be followed closely.

Hard Surface Linings

Portland Cement Concrete

Portland cement concrete can be used to line excavated pits or ponds and has various advantages over other linings. The lining can be used on steep, sloped pits (vertical walls possible--discussed later under "storage tanks"). It is not subject to damage by various mechanical means--vandalism, burrowing animals, and weeds--and generally the maintenance required is minimal. Concrete linings are subject to damage by alternate freezing and thawing, which may cause expansion and contraction of the concrete itself and movement of expansive subgrade soils. The lining is relatively expensive, depending on the site, and may be too costly if labor or transportation costs are excessive. If the lining is used in mild climates with proper subgrade soils and preparation, the disadvantages may be eliminated or at least minimized.

Information regarding installation procedures and concrete requirements for lining excavated pits is available (29). Information regarding concrete linings of irrigation canals (3, 18, 38) can also be used as guidelines. Panel-formed linings can be satisfactorily used unless sideslopes of the pit are greater than 1:1. Forms on steeper slopes must be used to support fresh concrete prior to curing. Reinforcing steel may be used, depending on the conditions. The concrete should be at least 4 inches thick. Panel sections may be as long as the screeding operation will allow, but 10-ft lengths are generally used. The bottom of the pit should be poured first and then the concrete screed up the sides. Various forms of water stops are available and should be used to create watertight joints. Cement content recommended varies from 5 1/2 to 6 1/2 bags per cubic yard, depending on the exposure conditions. On sites where sulfate concentration is more than 0.1 percent, special sulfate-resistant cements should be used (3).

Other Hard-surface Linings

Other types of hard-surface lining materials have been used, mainly in the lining of canals, with varying degrees of success. These have included pneumatically applied mortars (shotcrete), soil-cement, brick, and stones. Chances for successful use of either shotcrete or soil-cement depends mainly on their use in mild climates, where extensive freezing and thawing do not occur. Where inexpensive hand labor and materials are available, bricks or stones, mortared into place, may be used to line excavated pits. Experiences using these various lining materials have been reported (33, 38).

STORAGE BAGS

Storage bags constructed of butyl-coated nylon have been used both as one-piece or two-piece closed bags (20). The bags are confined to an excavated pit or basin with sideslopes not exceeding the angle of repose of the soil and no steeper than a vertical to horizontal ratio of 1:1 1/2. Such storage systems offer a completely closed system with both seepage and evaporation losses controlled.

One-piece bags are generally constructed of butyl-coated nylon, one-sixteenth inch thick. They are prefabricated from two pieces seamed along the edges, which are double thickness with grommets on approximately 6-ft centers. Guy wires are necessary for holding the bag in place when empty; they are fastened through the grommets and anchored to stakes around the perimeter of the basin.

Two-piece bags can be made onsite from two sheets of butyl. The sheets are generally one-thirty-second inch thick, and are laid in the pit and anchored around the top of the basin in a trench. Two-piece bags have several advantages over one-piece bags in that sheets can be maintained by uncovering the anchored edges, the sheets are easier to handle due to decreased weight, and costs are less since fabrication is not required.

All bags must be designed with a water inlet, outlet, and overflow outlet. One-piece bags require that these be fabricated into the system. With the one-piece bags, these features can be either fabricated into the sheets or the inlet and overflow designed in between the sheets. Size of storage is limited mainly by bag weight. One-piece bags are commercially manufactured to specifications with standard sizes up to 50,000 gal. Sheet for constructing two-piece bags can be prefabricated to any desired specification, with field splicing possible for very large installations.

Disadvantages regarding mechanical damage, vandalism, and various vermin are the same as noted earlier for synthetic rubber sheeting. A considerable amount of vermin damage was noted when observing these types of water storage systems over a 12-year period on the Fishlake National Forest in central Utah (11). There is a good possibility that such damage can be minimized if the area around the bag is properly managed.

Installation instructions are available from suppliers of materials used specifically for these water storage systems and should be followed carefully.

STORAGE TANKS

Storage tanks constructed of concrete and steel have been successfully used to store water associated with various stock-water developments. Tanks provide certain advantages that can not be attained with excavated pits. The ratio of water volume to containment or exposed surface area is a maximum with vertical sidewalls of a tank. Evaporative control devices, such as floating covers, can be more effectively and efficiently used on vertical-walled structures. Maintenance requirements are generally low and tanks can be easily repaired if damaged.

Tank sizes are limited somewhat, but are available commercially to 48-ft diameter and larger if so specified. Cost per unit volume of water stored may be high depending on the construction technique used. For large storage requirements, two or more tanks may be required.

Tanks can be constructed entirely above ground, partially buried, and, in certain instances, completely buried. If extensive excavation is required, the site selected for construction should be relatively free of rocks.

An inlet, outlet, and overflow must be provided for all tanks. How these are designed will depend on climatic conditions of the area and when the system will be used. If most of the precipitation is in the form of snow, an inlet must be designed to allow snowmelt to enter the storage system. Closed pipe conveyance systems from the water harvesting catchment to the storage system have failed to function properly in high snowfall areas (11). The storage outlet should be screened and adjustable. An adjustable outlet, taking water from near the top of the tank, protects against loss of the entire water supply in case of malfunction.

Water storage tanks generally do not need to be fenced, unless buried. If buried, a fence will be needed to keep livestock and game out of the tank. Bird ladders should be used with vertical walled tanks.

Watertightness of storage tanks has been achieved by use of puddled clay or bentonite, sodium chloride mixed in the earth bottom, concrete, and flexible membranes and films. Materials successfully used in construction of tank walls, along with bottom materials, will be briefly described.

Portland Cement Concrete

Portland cement concrete used for storage tank construction has basically the same advantages as those noted for lining excavated pits. Directions for installing circular concrete tanks have been presented by the Portland Cement Association (29). Items considered include effect of hydrostatic pressure with wall footing continuous and not continuous with the tank bottom--also constructed of concrete. Design instructions provide information regarding requirements for reinforcing steel and wall thickness. Generally, a wall with two curtains of reinforcement should not be less than 8 inches thick. Details are given regarding various footing designs as well as water stop and caulking requirements. Instructions on pouring concrete are also presented. Temperature stressing, due to expansion and contraction of concrete during normal atmospheric temperature fluctuation and contraction during curing, are also considered in the Portland Cement Association manual as well as by Olander (28).

Plastered Concrete

Tanks constructed of a concrete mortar have been successfully used in Arizona (39). The system consists of wire-reinforced walls plastered on both sides with concrete mortar inside of which is an unreinforced concrete floor of essentially the same mortar as that used for the sidewalls.

The tank construction procedure includes (1) constructing a double reinforcing cage of welded wire-reinforcing fabric around the required circle where the tank is to be built, (2) designing various inlets and outlets, (3) plastering the inside of reinforcing wall with approximately a 3/4-inch thick coating, (4) plastering the inside and outside of the wall core with a 1/2-inch coat of mortar, (5) constructing the floor, and (6) painting the inside wall and floor with an emulsified asphalt.

The concrete mortar consists of 1/4-inch maximum sized aggregate for the sidewalls, and 3/4-inch maximum sized aggregate for the floor. Construction time for an experienced one-man operation was estimated to be 9 to 10 days for a 20-ft-diameter tank 6 ft high.

Tank construction described is similar to a material referred to as ferrocement (27). The main difference is the form of reinforcing material used. Ferrocement uses a fine-meshed wire (chicken netting or plastering lathe) rather than welded wire reinforcement. The water-sand-cement mixture is essentially the same for both systems, both being hand applied. The emphasis of the ferrocement report refers specifically to developing countries where low-cost labor exists, but the material could be adapted to factory-fabricated components. More importantly, the common way of using the material, the do-it-yourself approach, can still be an attractive means of constructing water storage structures associated with water harvesting systems in many remote areas of developed countries.

Metal Tanks

Metal tanks can be all metal, both walls and floor, or partially metal, walls only, with some technique used to make the tank watertight. Steel plate has been commonly used in the construction of metal tanks. Conventional grain bins have recently been used successfully for water containment (10). The information regarding earth linings and chemical sealants described earlier in reference to excavated pits is applicable for use in sealing the bottoms of tanks. Concrete and flexible membrane liners have been used to attain watertightness in many instances.

Tanks constructed of steel plate are transported to field locations in sections and are assembled onsite by riveting, bolting, or welding. If a concrete base is used, the concrete should be reinforced and a concrete pad poured under the walls, extending outside the tank about 1 ft. Concrete should extend up the side of the tank rim about 6 inches. Emulsified asphalt or aluminum paint with an asphalt base should be used to coat the exterior of the tank, especially if the tank is partially buried.

Steel grain bins constructed of corrugated-galvanized sheet metal are also transferred to field sites in sections and assembled in the field. Bolts are used to fasten the bins together, The bins are generally partially buried to assure adequate wall strength. Concrete can be used for the bottom--similar to that described for steel plate tanks--or flexible liners can be used to maintain watertightness. PVC has successfully been used for this purpose, but it is subject to deterioration and may need to be periodically replaced. Synthetic rubber coated nylon, with a longer expected life than PVC, can be used as a liner for tanks. Various tank construction and liner materials are available commercially specifically for water storage.

Conventional grain bins can be supplied with a roof, which will result in a completely closed system, Such systems have been used (10) and are performing satisfactorily after 6 years' service.

Other Water Storage Tanks

Various other types of water storage structures have been used and are available. These include tanks constructed from wood, cinder block, and fiber glass polyester resin along with tanks from railroad cars, oilfield storage, and military surplus. Application of the constructed tanks to the storage of water from water harvesting systems has been limited. Use of the storage systems (railroad cars, oilfield, and surplus) should be considered when available at a reasonable cost.

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EVAPORATION SUPPRESSION FOR CONSERVING WATER SUPPLIES

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INTRODUCTION

Conserving water contained in existing storage facilities is, in many situations, the most economical means of providing additional usable water supplies. Evaporation of this stored water from open water surfaces may equal or exceed that used beneficially. Reducing evaporation losses is particularly desirable for several reasons. The water is already in the storage facility and, therefore, requires no transportation expense. The quality of the water is improved because the salts are distributed through a larger volume. No power, additional storage, or additional equipment, such as pumps, are needed. And, finally, no risk is involved in attempting to develop a new supply. The only cost involved is installing and maintaining an adequate method of evaporation reduction.

Although essentially discontinued since 1970, most evaporation-reduction research over the past 20 years has been with the use of monomolecular layers, or films, or long-chain alkanols. These films, although intriguing because of their low cost and ease of application, are not as effective as first anticipated, because they do not reduce incoming solar energy and cannot be maintained during windy periods. Evaporation reduction using monomolecular layers has averaged only about 20 percent in long-term field studies (1, 8, 11).

A more promising approach to evaporation reduction is to reduce the energy available for evaporation. The potential of these methods, to reduce the energy available for evaporation, is best illustrated by reviewing the results of studies reported in the literature. Generally, such methods reduce evaporation either by reducing the amount of solar energy entering the water or by reducing the transport of water vapor above the water surface. Solar energy entering the water is usually reduced by suspending a shade above the surface, providing a physical barrier on the surface, reflecting more of the incoming solar radiation than does a natural water surface, or by a combination of the above. Wind baffles placed around, on, or above the water surface have been used to reduce the transport of water vapor. Floating covers and suspended fabrics have reduced evaporation 60 percent to 95 percent in long-term field studies conducted on small ponds and tanks (2, 6, 7). Although these treatments initially cost more than monomolecular layers, they are much more efficient and last longer, so that the overall cost of the water saved is less. Reduction of water vapor transport has not been nearly as effective, with savings of only about 11 percent reported.

The objectives of this paper are to show that evaporation reduction can be an economical means of providing additional usable water, and to identify some of the more practical materials for reducing evaporation.

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EVAPORATION LOSSES

Estimates of evaporation from ponds and lakes are usually available for local National Weather Service facilities or from the literature (4, 14). Once the expected evaporation is known, it can be determined if saving all or part of this water would supply the additional water needed. In areas with high rainfall, or where other sources of water are readily available, evaporation control may not be practical. However, over much of the United States, evaporation losses exceed rainfall, and amount to over 36 inches per year. This is true for vast areas of grazing lands in the arid and semiarid Western United States. Hauling water to isolated stock tanks and ponds, although expensive, is the usual method of providing water in these grazing areas when spring runoff and summer rains supply insufficient water to carry livestock through the grazing season.

EVAPORATION REDUCTION METHODS

Once it has been determined that evaporation reduction can supply enough additional water to be worthwhile, the most effective method for the particular situation must be identified. The most effective method is to cover the entire surface with an impermeable material, but this is not always economical or practical. An analysis of the energy relationships of an evaporating surface indicated that evaporation would be reduced most by increasing surface reflectance to solar radiation, and by increasing long-wave radiation leaving or emitted from the evaporating surface; in other words, reducing the amount of energy available for evaporation (3). Reduction of the wind velocity should also reduce evaporation losses.

Since the emittance of long-wave radiation from a water surface and most other materials other than metals is above 0.90, the slight increase that could be achieved for this factor (0.90 to 1.00) would not alter the evaporation rate significantly. However, the reflectance of a water surface is low (0.07) and the range of reflectance for commonly used materials is wide (0.10 to 0.90). Therefore, a large increase in reflectance can significantly reduce the evaporation rate. The reflectance of a surface is generally related to its color--white or light-colored materials have a high reflectance and black or dark-colored materials have a low reflectance. Thus, it is desirable to make the water surface as light colored as possible.

Four main categories of energy-reducing treatments have been investigated: (1) coloring the water, (2) using wind baffles, (3) shading the water by suspended materials, and (4) placing floating materials on top of the water. Three of these treatments meet the criteria discussed above; that is, to make the surface a light color or to reduce the wind velocity directly above the water surface. Shading reduces not only the solar energy that reaches the water surface but also the wind velocity directly above the water surface, thus adding to its effectiveness. Certain floating covers reflect more of the incoming radiation than does a water surface and may also act as a physical barrier to evaporation.

The procedure for testing these various treatments has generally consisted of treating a small tank, or even a beaker, and comparing the evaporation rate with that from a similar untreated tank or beaker. If the treatment showed promise, larger tanks or small ponds were treated and the results noted. Rarely have these treatments been applied to large-scale sites.

RESULTS AND DISCUSSION

The results of investigations by various researchers are discussed under four main headings, which correspond to the method used to reduce the energy available for evaporation. These are: (1) changing the color of the water, (2) using wind barriers, (3) shading the water surface, and (4) using floating covers.

Changing the Color of the Water

Yu and Brutsaert (18) used very shallow evaporation pans to show the importance of the effect of color and reflectance on the evaporation rate. White pans evaporated 35 to 50 percent less than similar black pans. The use of dye to color the entire body of water, or dye mixed with oil to color only the surface layer, has not been nearly as successful. Gainer, Beard, and Thomas (12) reported savings of only 10 to 15 percent using dye, or an oil and dye mixture. Keyes and Gunaji (13) reported increases in evaporation of the same order of magnitude when blue dye was used to accelerate brine disposal.

Shallow white evaporation ponds, although effective in reducing evaporation losses, would be neither practical nor economical under most field conditions because of construction and maintenance problems. Dyes have not proved effective for reducing evaporation, because they do not sufficiently limit the solar energy entering, nor do they act as physical barriers.

Using Wind Barriers

Relatively few investigators have reported on the use of wind barriers to reduce evaporation. The energy-balance analysis indicated that reduction of the wind velocity alone usually would not produce large savings (3). This is supported by the results from a study using wind baffles, which reduced evaporation only 11 percent (7).

Shading the Water Surface

Shades to reduce the solar energy entering the water have been quite successful (table 1). Evaporation reduction has been about the same as the amount of shade provided.

The main problems encountered in using shading materials are: (1) They require some means of support to hold them above the water surface; (2) when attached to the supporting structure, some materials are placed under a strain or tension; and (3) the potential for wind damage is rather high. Supporting structures are of minor importance on small tanks where the shading material can be fastened to the edge or rim of the tank. However, on larger tanks or ponds, the supporting structure may cost as much as, or more than, the shading material itself, thus making this approach economically unacceptable. Tension or strain on plastic or rubber materials tends to increase the rate of deterioration at the point of strain, and reduce the effective life of the material. Minimizing the strain generally requires increasing the complexity of the supporting structure, which increases the cost and may offset the benefits. The shading material must be fastened to the supporting structure to reduce the potential for wind damage. Care in selecting the method of fastening can also help to reduce strain on the shading material.

TABLE 1.--Evaporation reduction achieved by various energy-reducing methods

Method	Area of water surface covered	Evaporation reduction	Literature Cited reference
	Percent	Percent	
(1) Changing the water color:			
Dye in water	100	6-9	(13)
Shallow, colored pans	100	1/ 35-50	(18)
(2) Using wind barriers:			
Baffles	-	11	(7)
(3) Shading the water surface:			
Plastic mesh	47	44	(7)
Blue polylaminated plastic sheeting	100	90	(10)
(4) Floating reflective covers:			
Perlite ore	78	19	(5)
Polystyrene beads	78	39	(15)
Wax blocks	78	64	(6)
White spheres	78	78	(7)
White butyl sheets	86	77	(3)
Polystyrene sheets	80	79	(3)
Polystyrene rafts	100	95	(2)
Continuous wax	100	87	(6)
Foamed butyl rubber	95	90	(9)

1/ Evaporation from white pan compared with that from black pan.

Floating Covers

Of the four energy-reducing methods discussed, floating covers have been the most widely researched. This is perhaps due to the encouraging results obtained, because many of them act as both reflectors and vapor barriers, and because of their easy application and low maintenance.

In general, covers can be divided into three types: (1) small individual particles such as perlite ore, polystyrene beads, wax blocks, and white spheres; (2) larger pieces such as polystyrene sheets, polystyrene rafts, and individual butyl sheets; and (3) a complete one-piece cover such as butyl sheeting or a continuous wax cover. The reflective properties of the third type are less important than those of the other types because there is essentially a complete vapor barrier.

Table 1 shows the evaporation reduction achieved by using various methods. One must be very careful in making comparisons, however, since results were obtained under different climatic conditions, and by using a variety of water-holding reservoirs, such as shallow evaporation pans, buried or insulated tanks, exposed wall tanks, and small lined ponds.

Each of the four small individual particle materials covered the same percentage of the water surface; however, the evaporation reduction efficiencies ranged from 19 to 78 percent. Both perlite ore and polystyrene beads were white, less than 1/4 inch in diameter, reflected about the same percentage of incoming radiation at the time of application, and became completely covered by a film of water. However, the albedo or reflectivity of the polystyrene beads remained about the same during the study, whereas the albedo of the perlite decreased to about one-third of its original value (15). Since the efficiencies early in the study were about the same, the decrease in efficiency of the perlite with time seems to correlate with the decrease in albedo. This decrease in reflectivity was probably due to the dust and algae that collected on the rough perlite particles, but did not accumulate on the rather smooth polystyrene beads. Both of these materials became covered with a film of water, causing them to be more like the shallow pans than like floating covers. In essence, they changed the color and reflectivity of the water and did not act as vapor barriers. Their efficiencies are also more representative of those in the group concerned with changing the color of the water.

The wax blocks (7) and white spheres (6) were larger (4 inches in diameter by 1 inch thick and 1 inch in diameter, respectively), and did not become wet on top. Both were white, providing a good reflective surface; both acted as vapor barriers, which added to their effectiveness.

The second type of floating covers, consisting of groups of larger pieces than those discussed above, reduced evaporation losses by about the same percentage as the percentage of the surface area covered (table 1). The three covers listed were all light colored and acted as both reflectors and vapor barriers. The slightly lower efficiency for the white butyl cover than for the polystyrene may be related to its insulating properties. The two polystyrene covers were between 1 and 2 inches thick and are good insulators; the white butyl was only 0.015 inch thick, which allows it to transfer heat quite readily. Sensible heat transfer from the warm air through the white butyl to the water during the day, therefore, may increase evaporation and reduce the efficiency of the cover slightly.

The third type of floating cover is a continuous cover made of thin film or sheeting material (6, 9). Reflective properties are much less significant than the ability of the film or sheeting to prevent vapor transfer, since the surface is almost completely covered or sealed. The continuous wax cover actually did seal the surface during warm weather, much like paraffin is used to seal jelly jars in home canning.

All of the floating covers discussed are subject to disruption or damage by wind. The small particles, such as perlite and polystyrene beads, tend to pile up or windrow, during windy periods, leaving portions of the water surface exposed. They do redistribute after the wind recedes, however, and again cover the entire surface. The lightweight white spheres would require steep banks and a few inches of freeboard or they would be blown off the surface entirely. The somewhat larger wax blocks have not been tested on large ponds, but they do not pile up like the smaller particles, and they have remained on stock tanks with only an inch of freeboard during winds of 50 miles per hour or more. These results suggest that wind may not be a critical factor in maintaining wax blocks on the water surface.

The white butyl and polystyrene covers must be anchored. In fact, the polystyrene rafts were designed to reduce wind problems. They are coated with cationic asphalt and coarse sand, much like a graveled roof, to add weight and weathering protection. The rafts are then joined together with simple (PVC) pipe connections to further protect the edges from wind. If protection or anchoring is not provided and the wind gets under one of these covers, they may fly from the pond like a large kite and be damaged considerably. The continuous or one-piece covers generally require the same protection, although the continuous wax cover has withstood winds of over 50 m/h on a stock tank with only 1 inch of freeboard. If a continuous wax cover should blow off a pond or tank, the damage would probably be minor since it could be placed back on the surface, even in small pieces, and it would re-form into a continuous layer once the temperature rose enough to remelt the wax.

VALUE OF SAVED WATER

The projected benefits of evaporation reduction must ultimately be based on the estimated value of the water that is saved, or cost of the procedure for saving it. Estimated costs for a variety of methods and materials can be found in the literature. However, these estimates are very difficult to use or compare, because of the rapid increase in the cost of equipment and labor since the estimates were made, and because of the variation in these factors in different locations at any given time. Analysis of the costs presented does indicate that five of the materials discussed will generally provide water for \$1 per 1.000 gallons or less in high evaporation areas. These five are wax blocks, butyl rubber, polystyrene rafts, continuous wax, and blue polylaminated plastic.

The continuous wax, polystyrene rafts, and butyl rubber are the most readily available and the least difficult to construct or apply. The wax blocks require special spray equipment and the blue polylaminated shade requires a supporting structure and is not available in all areas, making these two somewhat less practical.

Alternative supplies of water for stock tanks usually have been obtained by hauling water during dry periods. Costs of hauling water depend on the quantities hauled and the remoteness of the destination. A recent reference, and local accounts, indicate costs of \$15 per 1.000 gal where large volumes were transported (17). Costs to haul water to remote areas in small quantities probably are higher (16, 17).

Based on the above costs, evaporation reduction appears to be very economical. However, each case must be considered individually. Cost comparisons must be based on local costs and availability of materials. An example for central Arizona is presented below for illustration.

A rancher wants to graze cattle in an area approximately 4 mi^2 for about 90 days each year. A 25-foot-diameter by 6-foot-deep steel tank is installed near the center of the area so that the distance to water for the cattle is about 1-1/2 miles. Water is hauled to this tank in a 500-gal tank truck from water source about 4 miles away. A summary of the information with which he can determine the economics of reducing evaporation losses as compared with hauling water is presented in table 2.

As noted in this example, the rancher can save about \$55 a year by using a wax cover even if he has to replace it each year. Since some wax covers have been used more than 4 years with no apparent loss in effectiveness. he may be able to save considerably more. However, can the wax be recovered and reused after the tank goes dry? The use of the foamed butyl would cost the rancher an extra \$20 the first year, but it can be used for 10 to 15 years, even when the tank is dry part of the year. Initial savings with the gravel-covered polyethylene rafts would be slightly higher than with the foamed butyl. but total life would be slightly less, thus making overall savings about the same.

SUMMARY AND CONCLUSIONS

Reducing the solar energy entering a body of water, or reducing the transport efficiency above it, could reduce evaporation losses. The common methods of accomplishing this reduction are: (1) changing the color of the water; (2) placing wind barriers around or over the water:

TABLE 2.--Costs of hauling water with and without evaporation reduction

Water required

4 mi^2 x 640 acres/mi^2 = 2,560 acres.
Grazing capacity for 50 cattle 2,560 acres ÷ 50 cattle ÷ 3 months = 17 acres/animal unit month. About average for central Arizona.
Water used at 10 gal/head/day = 10 x 50 x 90 = 45,000 gal.

Evaporation losses

For May, June, and July = 0.35 inch/day (4).
Daily evaporation for 25-foot-diameter (490-ft^2 surface area) exposed wall tank (factors from reference 4 for exposed walls and central Arizona = 1.25 and 0.94, respectively) = 0.35 ÷ 12 x 490 x 1.25 x 0.94 x 7.48 = 125 gal/day.
Initial water hauled 1 week prior to need.
Total evaporation = 97 days x 125 gal/day = 12,000 gal.

Cost to haul water

Round trip = 8 miles.
Assume one round trip per hour for 500-gal tank truck (fill, haul, empty, and return).
Assume costs per round trip: Gas = $0.50
Maintenance = 1.50
Driver and water = 3.00
Total cost per round trip = $5.00

Cost to provide water supply without evaporation reduction

Total water required: 45,000 gal - cattle
12,000 gal - evaporation
57,000 gal

$\frac{57,000}{500} \times \$5 = \$570$ (This figure is very conservative compared with results from other studies (16, 17).)

Cost to provide water supply with 90 percent evaporation reduction

Total water required: 45,000 gal - cattle
1,200 gal - evaporation (12,000 - 0.90 x 12,000 = 1,200)
46,200 gal

$\frac{46,200}{500} \times \$5 = \$465$ (no partial trips)

Cost of covers (490 ft^2)

Wax	$ 50.
Gravel-covered polyethylene rafts	80.
Foamed butyl rubber	125.

Savings

Difference in hauling cost	$570 - 465 = $105.
Savings using wax cover	$105 - 50 = $ 55.
Savings using gravel-covered polyethylene rafts	$105 - 80 = $ 25.
Foamed butyl rubber--no initial savings	$105 - 125 = -$20.

(3) Shading the water surface; and (4) floating covers on the water. Evaporation has been reduced most (60 to 95 percent) by using floating covers and by shading the water surface.

The cost of the water saved by reducing evaporation compares favorably with costs of obtaining water from alternative sources. Four floating covers and one shade provided water for $1 or less per 1,000 gal in high evaporation areas, whereas costs of hauling water generally equaled or exceeded $15 per 1,000 gal. The continuous wax, polystyrene rafts, and butyl rubber are the most readily available and practical of the lower cost materials, although wind protection may be necessary in some cases.

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THE DESIGN OF ROADED CATCHMENTS FOR MAXIMUM RUNOFF

Malcolm Hollick [1]

ABSTRACT

This paper describes studies to improve the effectiveness of a formed water harvesting system known as the roaded catchment. These include the development of a method for calculating maximum nonerosive gradients for the channels and computer model studies to find the best catchment shape. The main conclusions are as follows: (1) The best width for plane-sided "roads" varies from about 1 to 6 m. (2) Corrugations, or "miniroads," on the sides of the roads are valuable, and, in this case, the optimum width ranges from about 6 m to the limits of economical construction. (3) Roads should never be shorter than the length that gives a square catchment layout, and, in many cases, should be longer than this.

INTRODUCTION

To provide reliable runoff, a water harvesting catchment needs to be impermeable, smooth, and have little depression storage. However, sealing the soil surface is expensive, and some infiltration losses must frequently be accepted. In these cases, ground forming can increase the runoff yield by improving the hydraulic efficiency of the catchments and thus reduce the time available for infiltration to take place.

One type of formed catchment that is widely used in Western Australia, and to a lesser extent in other States, is the so-called roaded catchment. This consists of a series of parallel formed and compacted roads with exaggerated camber that adjoin to make approximately V-shaped channels, which discharge into a collecting drain at their lower end (fig. 1) (1, 3).

The roaded catchment was developed from field experience, and design rules-of-thumb were produced for road and collecting channel gradients to ensure that serious erosion would not occur (3). However, these rules do not consider differences in soil erosion resistance or rainfall intensity and thus, to be effective, must generally give very conservative results. Also, the size and shape of the roads and type of catchment layout were determined by intuition and available construction equipment, rather than by an analysis of the hydraulic efficiency.

This paper presents a necessarily brief description of research at the University of Western Australia aimed at improving the effectiveness of the roaded catchment. This includes the development of a physically based method for the calculation of maximum nonerosive channel gradients and computer model studies of the influence of catchment design parameters on the runoff yield.

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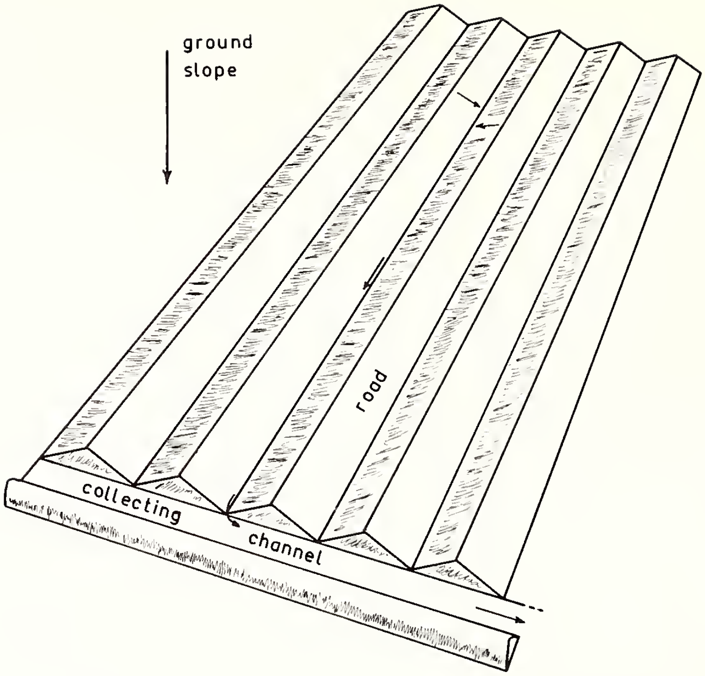


FIGURE 1.--Idealized roaded catchment.

DESIGN OF MAXIMUM NONEROSIVE CHANNEL GRADIENTS

Design Equations

For all but relatively deep, narrow channels, the maximum tractive force occurs on the bed and may be approximated by,

$$\tau = \rho g y S_o \qquad (1)$$

where τ = bed shear stress exerted by the flow, ρ = density of water, g = acceleration due to gravity, y = flow depth, and S_o = channel gradient (2). If values for the critical tractive force for the soil (τ_c) and the maximum flow depth can be estimated then equation 1 can be used to calculate the maximum nonerosive channel gradient.

The maximum expected flow rate in a channel fed by a catchment is $C.A_c.q$, where A_c is the upstream catchment area and q is the maximum expected rainfall intensity for a duration equal to the time of concentration of the catchment to that point and for the design return period. For roaded catchment, C may be taken as 1.

Using Manning's formula for flow in a channel, therefore,

$$A_c.q = \frac{\sqrt{S_o}}{n} R^{2/3}.\ A \qquad (2)$$

when n = Manning's roughness coefficient, R = hydraulic radius of the channel, and A = cross-sectional area of flow in the channel.

Both A and R are functions only of the flow depth and the channel cross section shape, and hence for any given channel equation 2 can be used to estimate the maximum flow depth in equation 1.

Three different channel types are used in roaded catchments as shown in figure 2: the V-channel formed by the road surfaces, a V-collecting channel, and a trapezoidal collecting channel. Both the V-channels are shown enough that,

$$R \approx y/2 \qquad (3)$$

and

$$A = y^2.\cot\theta$$

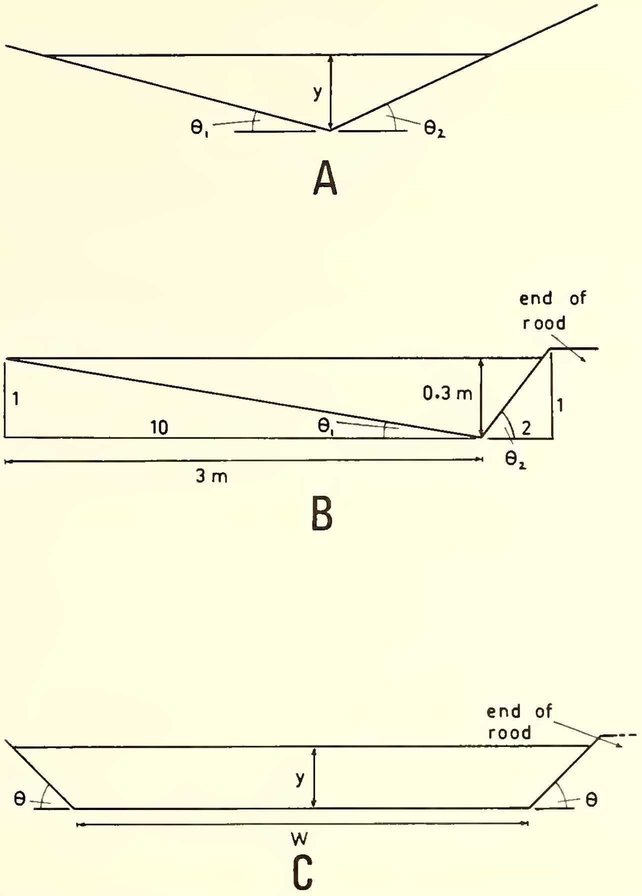


FIGURE 2.--Channel types used in roaded catchments: A, V-channel formed by roads; B, V-collecting channel; and C, trapezoidal collecting channel.

where $\cot\theta = (\cot\theta_1 + \cot\theta_2)/2$; and θ_1, θ_2 are the angles between the sides of the channel and the horizontal (that is, the side slopes are $\tan\theta_1$, $\tan\theta_2$).

Substituting for A and R using equations 3 and 4; and for y using equation 1; therefore, equation 2 becomes,

$$S_o = 0.6 \times 10^{-4} \, \tau_c^{16/13} \left(\frac{\cot\theta}{A_c \cdot q} \right)^{6/13} \tag{5}$$

This is directly soluble for the maximum safe gradient provided values of τ_c, θ, A_c, and q are known.

Similarly for the trapezoidal channel,

$$A = y(W + y\cot\theta) \tag{6}$$

and

$$R = y\,\frac{(W + y\cot\theta)}{(W + 2y\,\mathrm{cosec}\,\theta)} \tag{7}$$

where W = channel bed width. In this case, however, substitution of equations 1, 6, and 7 in equation 2 does not yield an equation that is directly soluble for S_o, and in the computer model studies an iterative solution had to be obtained. However, direct nomographic solution is possible, and nomograms for the design of both V- and trapezoidal channels on roaded catchments are to be published elsewhere.

The factor $q^{6/13}/\tau_c{}^{16/13}$, which appears in equation 5 and also occurs in the design of the trapezoidal channel, combines the influences of rainfall intensity and soil erosion resistance into what is called the "erosion hazard" in the remainder of this paper. It uniquely defines the gradients to be used in any catchment once the channel shapes and sizes have been determined. However, q also has an independent effect in determining the necessary channel size.

Application of Design Equations

Before the design equations given above can be used, it is necessary to be able to estimate suitable values of the maximum rainfall intensity and soil critical tractive force. Both of these factors present some problems and are discussed below.

Selection of Design Rainfall Intensity

Since roaded catchments are usually designed and surveyed at approximately 20-m intervals, a variable rainfall intensity corresponding to the changing time of concentration should ideally be used. However, this is not practicable because of the very short times involved, which for individual roads are usually less than 5 minutes.

It is, therefore, suggested that a rainfall intensity for a duration of 5 minutes and a return period of 5 or 10 years should be used for the whole catchment. As a result, upstream sections of the roads may be too steep, but damaging rainfall events should be of sufficiently short duration and rate occurence for erosion to be negligible.

Assessment of Critical Tractive Force for the Soil

Paaswell (6) recently stated that "generally used soil classification indexes have not proved useful as erosion predictors," and no satisfactory specialized test is currently available. The author is working on the development of such a test for use in roaded catchment design, and until this is available application of the methods described above will be restricted.

Slope Erosion

Observations on several recently constructed roaded catchments with widths up to 24 m indicate that rilling of the side slopes may, in fact, be a more serious problem than channel erosion. No design method has been produced yet, but it should be possible to derive length/steepness guidelines based on the soil erosion resistance test.

COMPUTER MODEL OF THE ROADED CATCHMENT

The runoff yield from a roaded catchment is influenced by many interrelated factors, and it would be almost impossible to determine the effect of each of these experimentally. Thus, it was decided to develop a computer model for this purpose.

Simulation of the Roads

A catchment surface may be simulated to any desired degree of accuracy by dividing it into a number of plane elemental areas. Each element can be assigned suitable values of size, slope, surface roughness, depression storage, and infiltration rate and may be assumed to have a uniform depth and velocity of flow at any time. The flow over the whole surface can then be calculated by applying the continuity and simplified momentum equations (rating function) to each element in turn for a small time increment. For this model, the Darcy-Weisbach formula for laminar flow and the Manning formula for turbulent flow were used with the equation of continuity in the form,

$$I_1 + I_2 - Q_1 + 2S_1/\Delta t = 2S_2/\Delta t + Q_2 \qquad (8)$$

where I = inflow rate to element, Q = outflow rate from element, S = S = volume of water stored in the element, Δt = time increment, and subscripts 1 and 2 denote values for the start and finish of the time step, respectively.

Knowing the depth of flow in all elements at time t_0, and starting with the highest element on the surface (where inflow from adjacent elements is zero), the outflow rate to adjacent downstream elements at $t_0+\Delta t$ can be calculated. The solution for $t_0+\Delta t$ can then be advanced over the surface by successive applications. The initial condition is usually that of no flow.

The actual sizes of the overland flow surface of the road and the channel formed by it are a function of the depth of flow in the channel. At the start of each run, the channel is assumed to consist of the bottom row of surface elements on each side, and more elements are removed from the surface and added to the channel as required. This system is rather crude, and a refinement would be to use variable width elements at the boundary of the surface and channel. However, this was not considered necessary since the width of the elements used had little influence on the resultant hydrograph.

Calculation of the channel flow was done in an exactly analogous way to that for overland flow except that channel length segments rather than area elements were used.

Simulation of Collecting Channels

The method outlined above for the roads is a difference solution of the kinematic wave approximation to the equations for unsteady flow with lateral inflow and outflow. This approximation assumes that all terms, except the friction slope in the momentum equations, are small compared with the channel gradient. However, it was found with the collecting channels that the lateral inflow could be high enough for this to be invalid. Thus, it was not possible to use a simple rating function for the momentum equation and additional terms for the water surface slope and the acceleration of the incoming flow had to be included. These effectively formed a variable correction to be subtracted from the channel gradient in the Manning formula, before proceeding with the solution as described above.

Complete Model

For convenience, the model was developed in two parts. The first designs the road gradients using equation 5 and then calculates the outflow hydrograph for the road. The second designs the collecting channels and then uses the outflow hydrograph from the road to calculate the hydrograph for the whole catchment. Since results were required for a large number of catchments in this study, runs were usually made for long roads or large catchments and results for smaller sizes were produced simultaneously. Simplified flow charts for the two programs are given in figures 3 and 4.

Model Accuracy

Field verification has not been possible due to a lack of data. However, one reason for using this type of model was that Huggins and Monke (4) had already used it to simulate small natural catchments with some success. More recently, Wilke et al. (7) used a similar model to

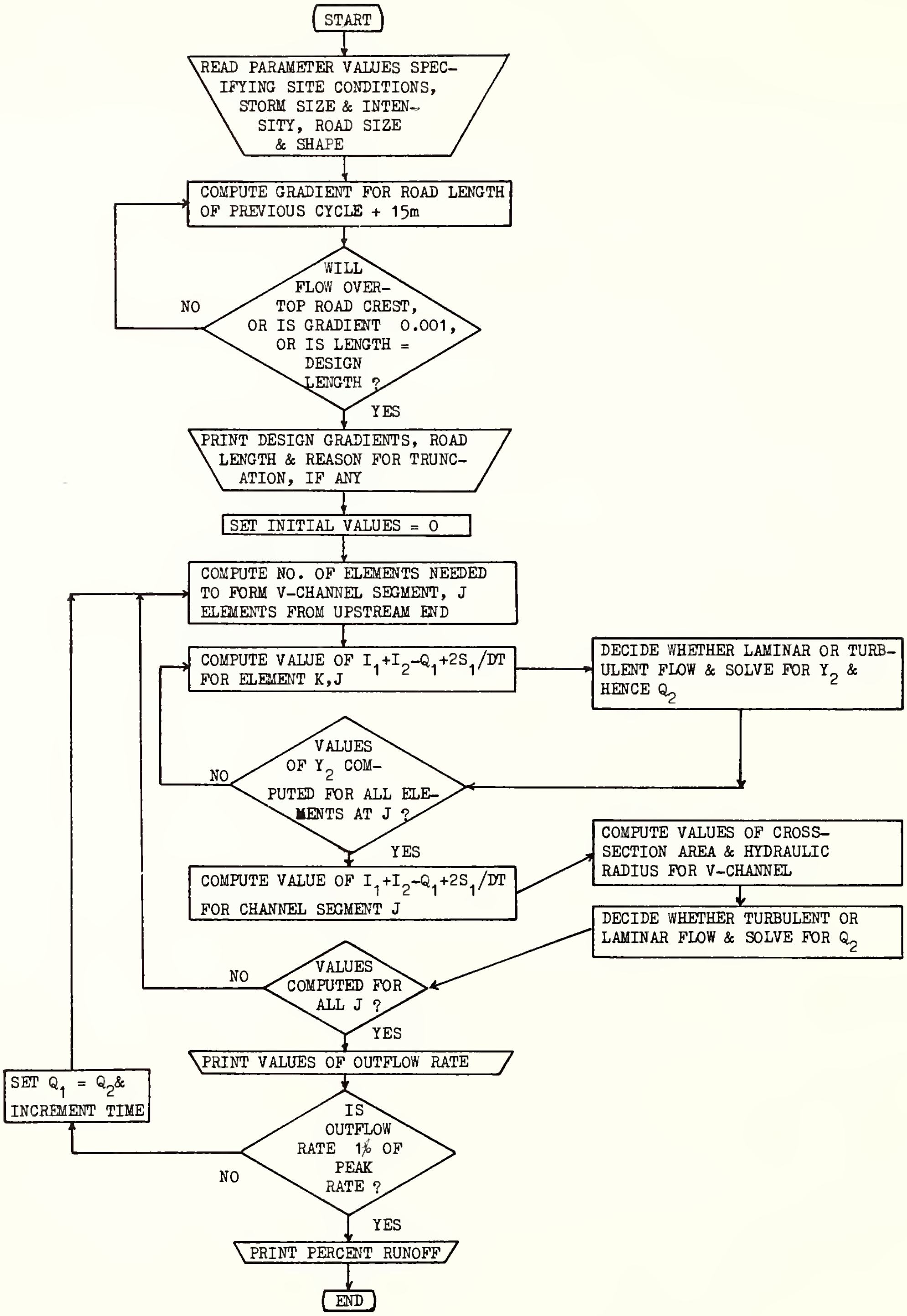

START
READ PARAMETER VALUES SPECIFYING SITE CONDITIONS, STORM SIZE & INTENSITY, ROAD SIZE & SHAPE
COMPUTE GRADIENT FOR ROAD LENGTH OF PREVIOUS CYCLE + 15m
WILL FLOW OVERTOP ROAD CREST, OR IS GRADIENT 0.001, OR IS LENGTH = DESIGN LENGTH ?
NO
YES
PRINT DESIGN GRADIENTS, ROAD LENGTH & REASON FOR TRUNCATION, IF ANY
SET INITIAL VALUES = 0
COMPUTE NO. OF ELEMENTS NEEDED TO FORM V-CHANNEL SEGMENT, J ELEMENTS FROM UPSTREAM END
COMPUTE VALUE OF $I_1+I_2-Q_1+2S_1/DT$ FOR ELEMENT K,J
DECIDE WHETHER LAMINAR OR TURBULENT FLOW & SOLVE FOR Y_2 & HENCE Q_2
VALUES OF Y_2 COMPUTED FOR ALL ELEMENTS AT J ?
NO
YES
COMPUTE VALUE OF $I_1+I_2-Q_1+2S_1/DT$ FOR CHANNEL SEGMENT J
COMPUTE VALUES OF CROSS-SECTION AREA & HYDRAULIC RADIUS FOR V-CHANNEL
DECIDE WHETHER TURBULENT OR LAMINAR FLOW & SOLVE FOR Q_2
VALUES COMPUTED FOR ALL J ?
NO
YES
PRINT VALUES OF OUTFLOW RATE
SET $Q_1 = Q_2$& INCREMENT TIME
IS OUTFLOW RATE 1% OF PEAK RATE ?
NO
YES
PRINT PERCENT RUNOFF
END

FIGURE 3.--Flow chart for roaded simulation program.

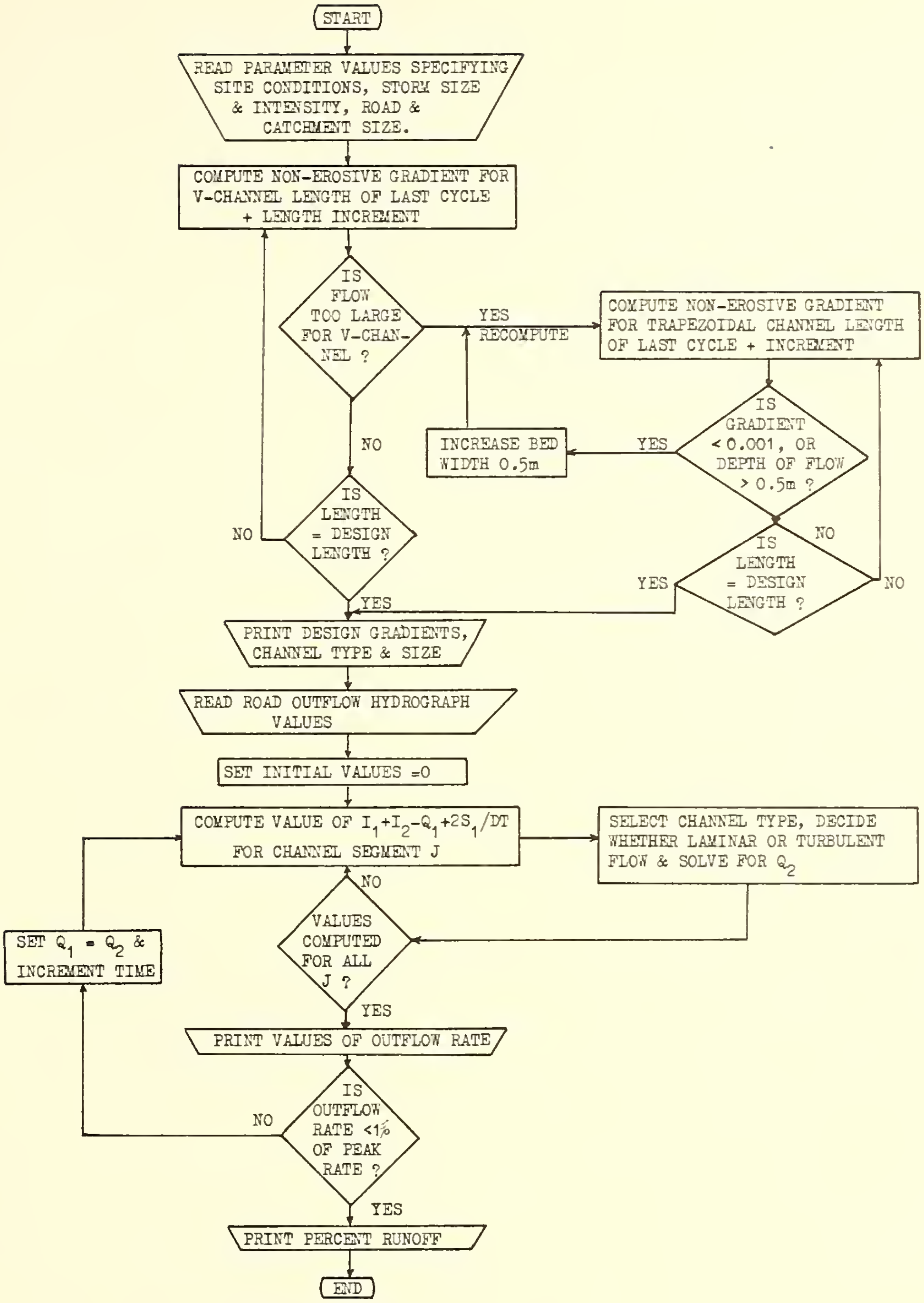

START
READ PARAMETER VALUES SPECIFYING SITE CONDITIONS, STORM SIZE & INTENSITY, ROAD & CATCHMENT SIZE.
COMPUTE NON-EROSIVE GRADIENT FOR V-CHANNEL LENGTH OF LAST CYCLE + LENGTH INCREMENT
IS FLOW TOO LARGE FOR V-CHANNEL ?
YES RECOMPUTE
COMPUTE NON-EROSIVE GRADIENT FOR TRAPEZOIDAL CHANNEL LENGTH OF LAST CYCLE + INCREMENT
IS GRADIENT < 0.001, OR DEPTH OF FLOW > 0.5m ?
YES
INCREASE BED WIDTH 0.5m
NO
IS LENGTH = DESIGN LENGTH ?
YES
NO
NO
IS LENGTH = DESIGN LENGTH ?
NO
YES
PRINT DESIGN GRADIENTS, CHANNEL TYPE & SIZE
READ ROAD OUTFLOW HYDROGRAPH VALUES
SET INITIAL VALUES =0
COMPUTE VALUE OF $I_1+I_2-Q_1+2S_1/DT$ FOR CHANNEL SEGMENT J
SELECT CHANNEL TYPE, DECIDE WHETHER LAMINAR OR TURBULENT FLOW & SOLVE FOR Q_2
NO
VALUES COMPUTED FOR ALL J ?
YES
SET $Q_1 = Q_2$ & INCREMENT TIME
PRINT VALUES OF OUTFLOW RATE
IS OUTFLOW RATE <1% OF PEAK RATE ?
NO
YES
PRINT PERCENT RUNOFF
END

FIGURE 4.--Flow chart for collecting channel simulation program.

simulate individual roads and obtained reasonable agreement between their calculated and measured hydrographs. However, they obtained values for the surface roughness and infiltration parameters by optimization, but did not include depression storage; so, their results may not be reliable.

Test runs indicated that the model converges to a steady solution as the difference grid is refined, and it proved stable over a wide range of time steps. However, failure eventually occurs if the time step is made too long. For most cases, 15- to 30-second steps are suitable.

MODEL STUDIES OF OPTIMUM CATCHMENT SHAPE

When a roaded catchment is to be constructed, the ground slope and rainfall pattern are totaly determined by the site, and the hydraulic roughness, erosion hazard, and infiltration characteristics largely so, unless chemical treatment of the soil is to be used. Thus, the designer only has control over the depression storage--length, width, and side slope of the roads--and the overall size and shape of the catchment. Of these, the last two are largely determined by the site conditions, choice of road length, and amount of runoff required. It is clearly advantageous to use the steepest side slopes and smoothest surface possible to minimize depression storage and increase the runoff velocity. Hence, the choice is effectively reduced to two parameters--road width and road length. However, the optimum values for these may be influenced to a greater or lesser extent by all the other factors.

In view of this, it was found most convenient to plot the results for individual roads as runoff percent versus road width for a range of road lengths and with all other factors held constant. The resultant curves for the conditions given in table 1 are shown in figure 5. These have a typical shape with a distinct maximum and a more rapid drop on

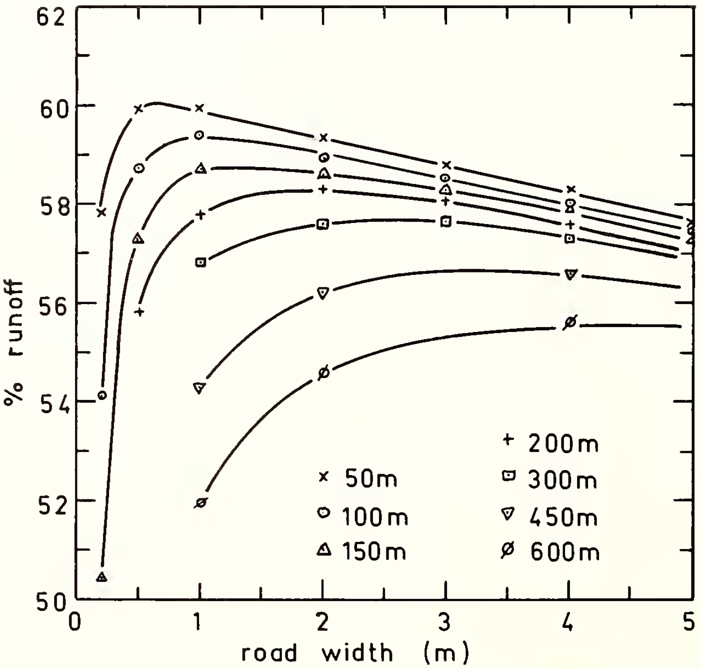


FIGURE 5.--Percent runoff versus road width for range of road lengths for conditions given in table 1.

the narrow road side of the peak than on the wide side. However, modeling errors and the need to limit the number of computer runs made it impossible to select optimum width values with any confidence. It was thus decided to bracket the optimum by selecting those points at which the runoff had fallen about 1 percent below the peak value and to replot the results as upper and lower width bounds on a width versus length plot as shown in figure 6. Again, these results are typical with the bounds rising and diverging with increasing road length. Response of the system was then studied by determining the effect on these width bounds of varying each of the parameters given in table 1 in turn.

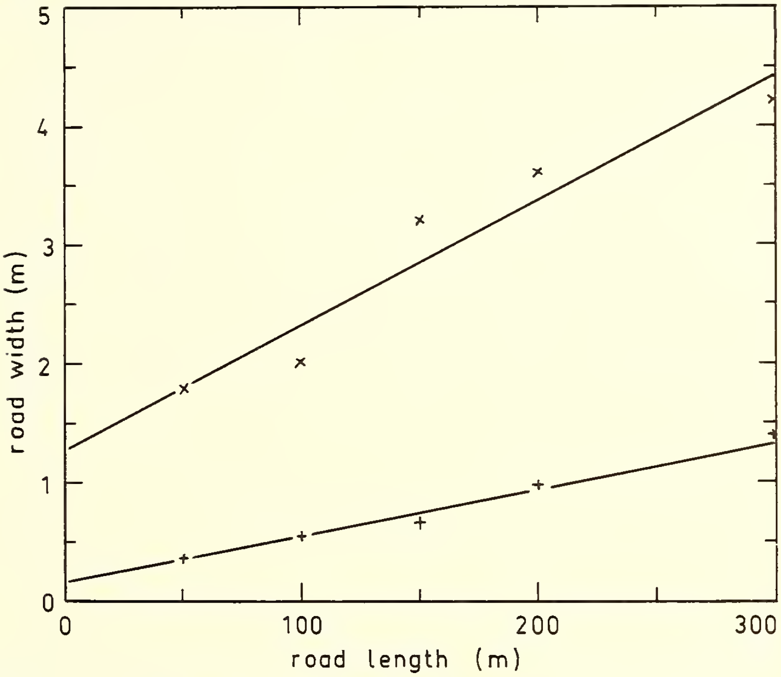


FIGURE 6.--Optimum width bounds for conditions given in table 1.

Influence of Various Factors on Optimum Road Width

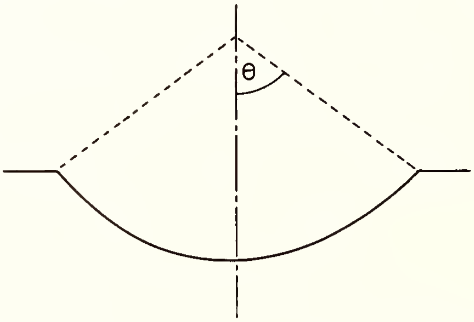
Depression Storage

Although the model was written to include depression storage in the form of geometric hollows, it was decided not to include it as a variable because very little is known about its depth and characteristics on roaded catchments. However, general conclusions can still be drawn if it is assumed that all depression storage must be satisfied before runoff can start. In this case, the effect is similar to that of reduced storm duration which is discussed below.

The success of the roaded catchment is at least partly due to the reduction in depression storage obtained by using very steep side slopes, but no data are available on the magnitude of this effect. An attempt has been made to gain some understanding by analysing the change in capacity of 24 geometric shapes of depression as the surface in which they are formed is tilted from the horizontal. Figure 7 defines the depressions used: eight sphere caps, eight circular cross-section ruts, and eight V-ruts. Figure 8 shows mean curves of percent capacity on flat ground versus ground slope for the 24 depressions and for the 12 shallower

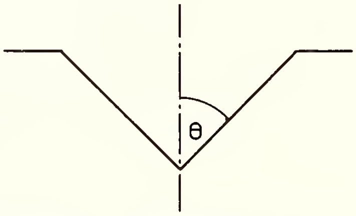
TABLE 1.--Standard catchment and storm parameters

Parameter	Value	
Surface hydraulic roughness	Laminar flow (Darcy) K = 30 Turbulent flow (Manning) n = 0.02	
Road side slope	20% (plane)	
Ground slope	2% (plane)	
Soil critical tractive force	38 Newtons/m^2 (0.8 psf)	) low
		)
Design maximum rainfall		) erosion
		)
Intensity	75 mm/h	) hazard
Constant infiltration rate	2.5 mm/h	
Depression storage	0	
Storm intensity	7.5 mm/hr	
Storm duration	10 min	



Types 1–16: sphere caps & circular cross-section ruts.

θ = 2,5,10,20,30,50,70,90 degrees.



Types 17–24: triangular cross-section holes or ruts.

θ = 45,55,65,75,80,85,88,89 degrees.

FIGURE 7.--Definition of depression shapes.

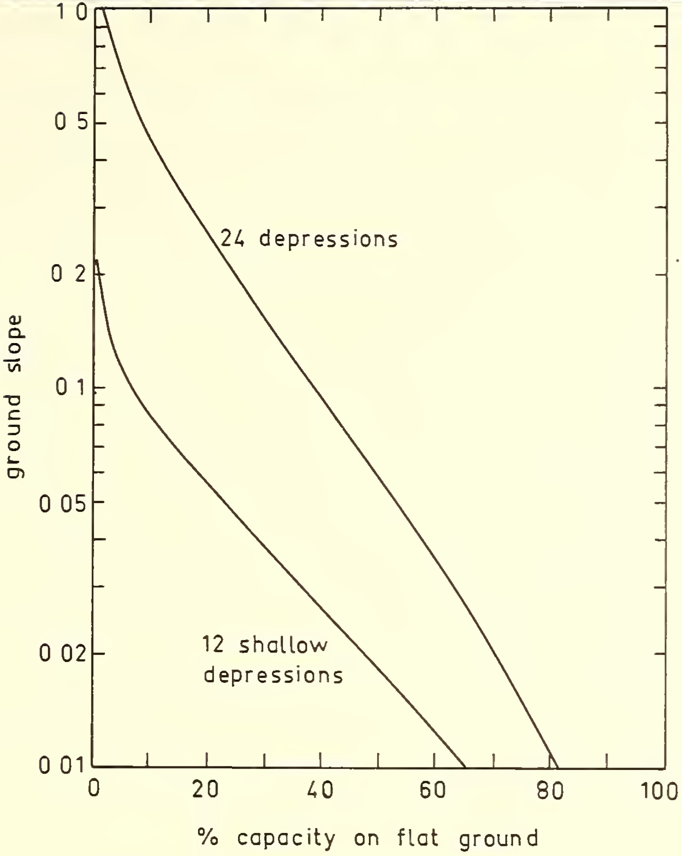


FIGURE 8.--Change of depression storage with surface slope.

types. These indicate that substantial reductions in depression storage may occur up to a slope of at lease 20 percent and perhaps as high as 100 percent.

Infiltration Rate

Infiltration is a complex process, and it was difficult to simplify it sufficiently for this study and still be able to draw valid conclusions. Figure 9 gives results for various steady infiltration rates representing the final intake rates that exist when the catchment is saturated. As the infiltration rate increases the lower bound rises, and the effect of road length increases (that is, the lower bound lines diverge). The behavior of the upper bound is similar except that the effect of road length is more marked. Thus, for short roads the found falls with increasing infiltration rate, but it rises for longer roads. A similar pattern was also shown by results for a rainfall intensity of 30 mm/h and infiltration rates of 10 to 25 mm/h.

Short, wide roads have a shorter recession time than long narrow ones, but the wetted area is not so rapidly reduced after the end of rainfall. It appears that as the infiltration rate is increased the additional losses from the concentrated channel flow on long roads outweigh those from the longer overland flow slopes of the wider roads, thus moving the optimum towards wider roads.

To satisfactorily categorize variable infiltration, requires the use of at least three independent parameters, and the additional computing needed to do this was not considered justified. However, two general conclusions can be drawn if the total volume of water lost to infiltration is taken as a basis for comparison. Where the total loss in each case is the same, the optimum width for the variable rate case would be lower than for the steady case; and the loss of yield with

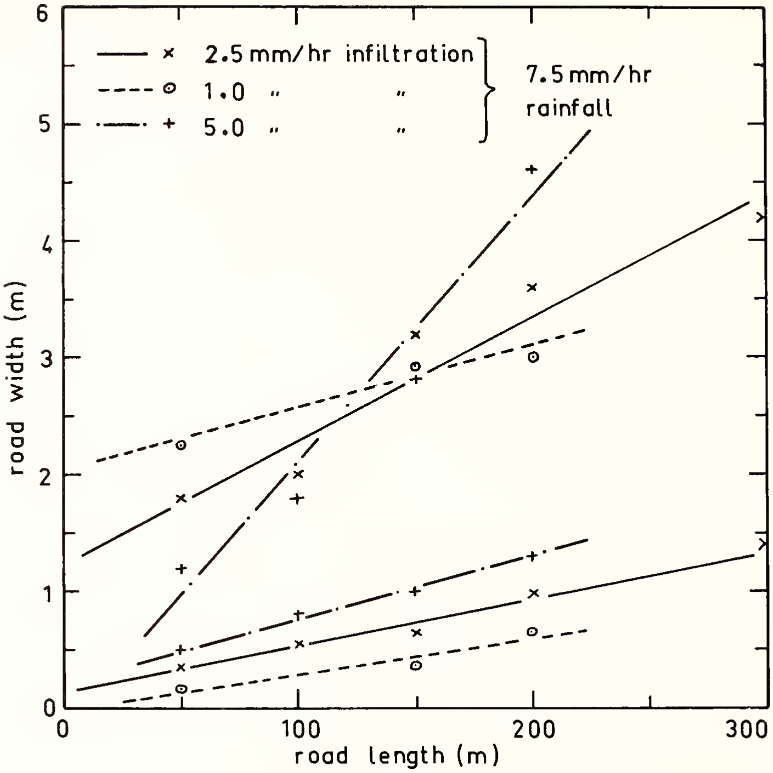


FIGURE 9.--Effect of infiltration rate on optimum width bounds.

increasing road length would also be less. These are both due to the fact that losses from the concentrated recession flow are lower for the variable rate because of the decrease in the rate with time.

Ground Slope

Figure 10 shows the influence of ground slope on the width bounds to be considerable. As the ground slope increases, the optimum width decreases and the range of suitable widths narrows. This is a clear effect of the V-channel becoming relatively more efficient than the side slopes as its gradient increases.

Erosion Hazard

The effect of erosion hazard is closely linked with that of ground slope since it is at the higher ground slopes that its influence is most apparent. Figure 11 shows the same results as figure 10 for ground slopes of 2, 5, and 8 percent, plus those for roads designed for a high erosion hazard (rainfall intensity 200 mm/h, critical tractive force 9.5 Newtons/m^2) instead of the low one used as standard. Once the roads become large enough for the difference to be evident, the bounds start to rise more steeply with length than for the low hazard case. This is because the gradients become limited by erosion considerations rather than the ground slope, thus making the V-channels relatively less efficient than the side slopes. Values for 15-percent ground slope and long roads at 8 percent are not given because satisfactory designs are not possible at the high erosion hazard.

It is also of interest to assess the likely effect of erosion hazards

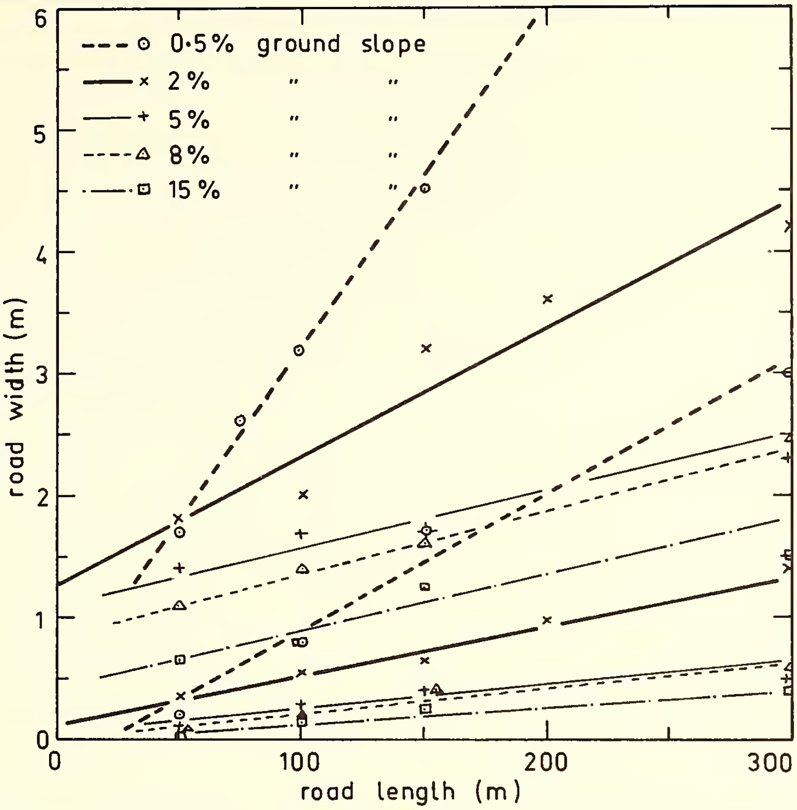


FIGURE 10.--Effect of ground slope on optimum width bounds.

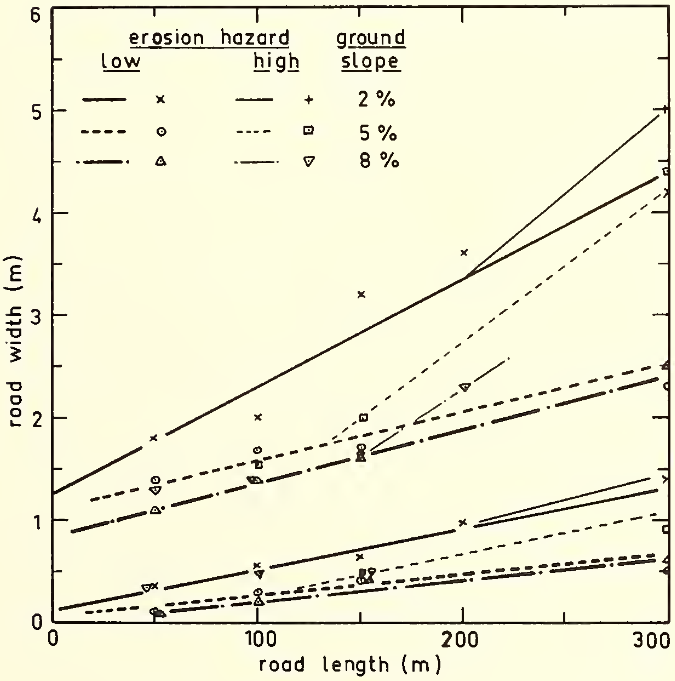


FIGURE 11.--Effect of erosion hazard on optimum width bounds.

on the runoff yield, since this will indicate the value of using the design methods for the maximum nonerosive gradients given above. Figure 12 shows the effect of road gradient on runoff yield for the standard storm, and indicates that below about 2 percent it is of some importance. Clearly, the effect would not be so large on an annual basis when storms of higher intensity and longer duration would be included, but nevertheless worthwhile gains could be made in marginal runoff conditions. Also, the steeper gradients would result in less ponding in the channel, and more of the detritus that collects in the V-channels would be flushed from the catchment, thus reducing losses.

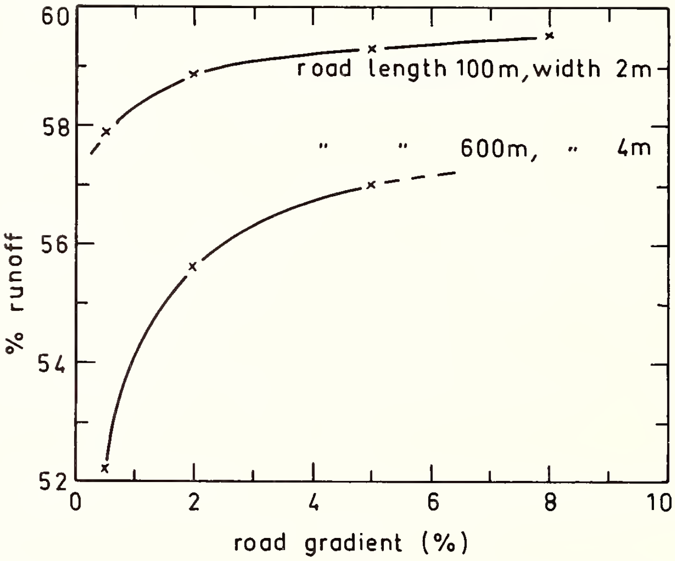


FIGURE 12.--Effect of road gradient on percent runoff.

Road Cross Section Shape

The runoff percentages obtained for the standard conditions are plotted against road length for no side slope and a side slope of 20 percent in figure 13. This demonstrates the superiority of the roaded catchment over ground that has simply been smoothed and compacted. For very short roads or overland flow distances, the two types do not differ greatly, but as the length increases the yield from the smoothed ground falls rapidly, whereas that from the roads remains relatively constant. The differences would be less for a lower infiltration rate, more intense or longer duration storm; but would be greater if depression storage were considered because of the difference in surface slopes.

The influence of plane road side slopes between 10 and 100 percent on the optimum width bounds was found to be quite small, with both the upper and lower bounds falling with increasing side slope. In practice, this effect would possibly be obscured by the drop in depression storage resulting from the increased slope. This would have the same effect as an increase in storm duration, which causes the bounds to move apart, thus possibly giving the greatest range of acceptable widths at steep side slopes rather than vice versa.

Some roaded catchments have been installed with rounded bottoms to the road channels instead of a sharp V to reduce the risk of erosion.

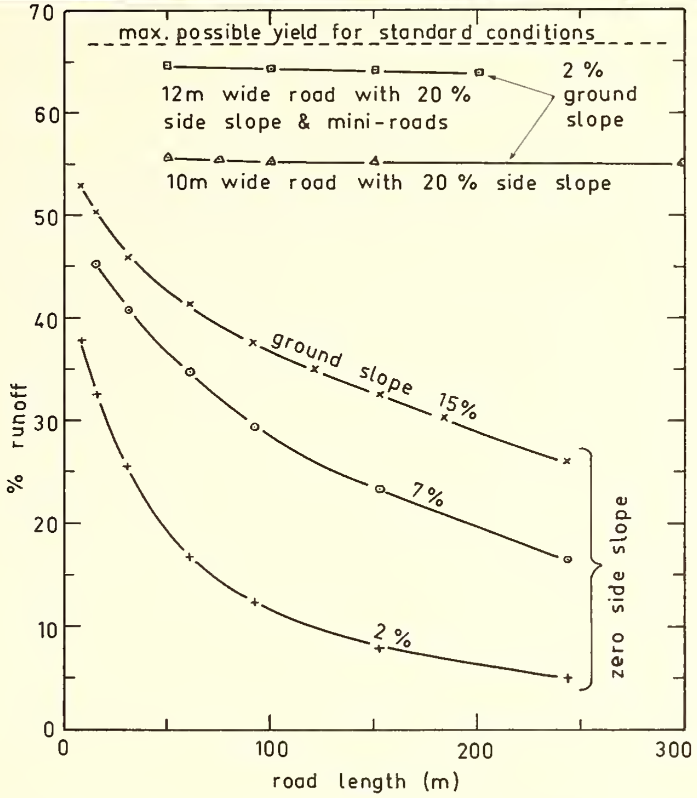


FIGURE 13.--Comparison of percent runoff from roads with zero and 20 percent side slopes.

This reduces the yield in the standard storm by 3 to 5 percent, and the difference would be greater if depression storage were included. Thus, provided suitable nonerosive gradients can be determined, this technique cannot be recommended.

Storm Intensity and Duration

As might be expected, the bounds move apart, and hence the width becomes less critical as the storm intensity or duration is increased.

Surface Hydraulic Roughness

The influence of this is small, with increased roughness tending to raise both the upper and lower bounds slightly.

"Miniroads"

Experiments have been conducted in Western Australia with the formation of corrugations, or "miniroads," on the side slopes of the roads. A square roller with approximately 0.5 m sides has been used for this with some success. Computer simulation indicated that the optimum width might be as low as 0.1 m and that the cross section shape does not have a very large influence. Runoff percentages for roads incorporating miniroads are shown in figures 13 and 14. Maximum yields are increased by 7 to 10 percent, but the most interesting fact is that the yield versus width curves are flattened, and the peaks moved toward wider roads compared with those without corrugations. Thus, there is a much greater range of acceptable widths, and these correspond quite well with those currently used in practice.

Recommended Road Width

Despite the variability of the optimum widths for ordinary roads, one clear conclusion can be drawn: They should generally be narrower than the 6 to 30 m currently in use. This is illustrated in figure 15,

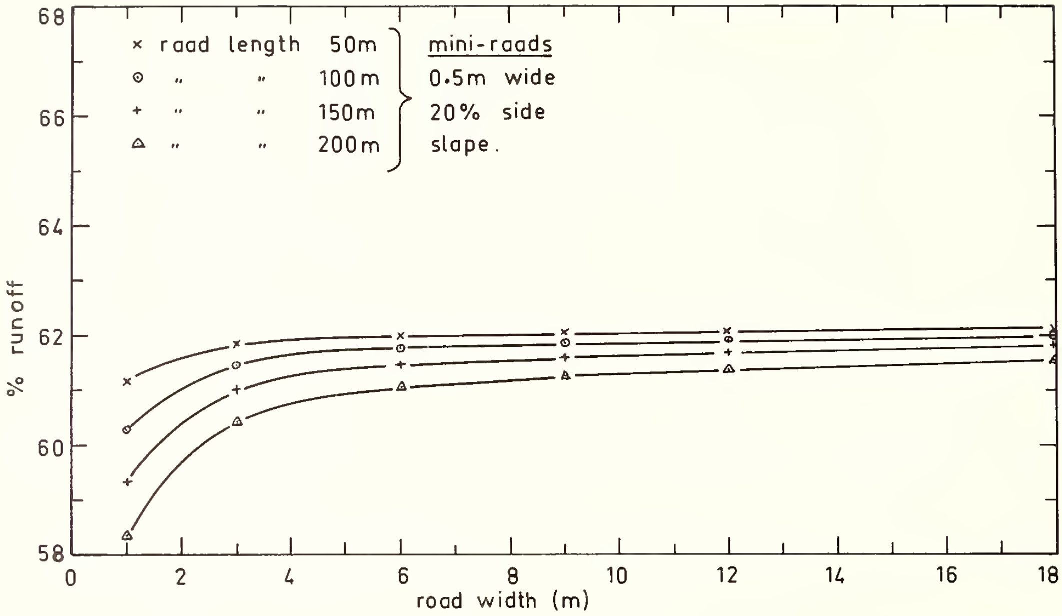


FIGURE 14.--Percent runoff versus road width for roads with miniroads.

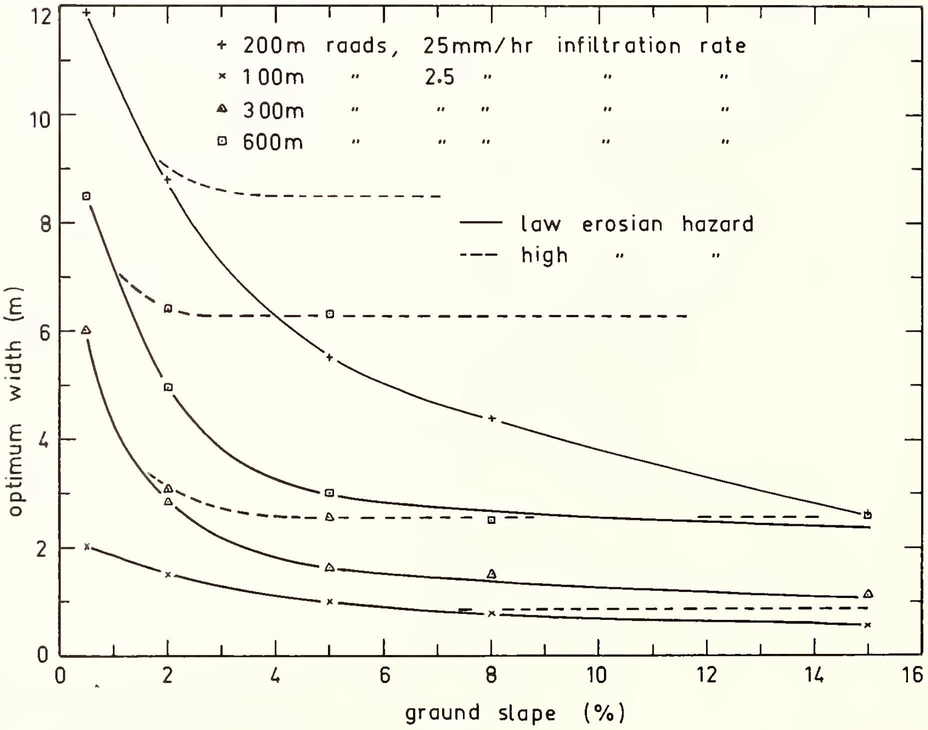


FIGURE 15.--Mean optimum widths for range of conditions.

where mean optimum widths (that is, average of upper and lower bound widths) have been plotted against ground slope for a range of conditions. Surface roughness and side slope were omitted as they have relatively little influence, and a short duration, low intensity storm was selected because the same widths would be acceptable for longer, more intense events. The majority of results given are for an infiltration rate of 2.5 mm/h, but one set for 25 mm/h is given for comparison. This shows that the infiltration rate has a major influence on the optimum road width, but unfortunately it is not known what infiltration rates occur on typical roaded catchments. However, 2.5 mm/h is probably close to the upper limit for a successful catchment. Until field data are available, the best that can be done is to use the 2.5-mm/h results as representative and make recommendations accordingly. It is thus suggested that the widths given in table 2 may be best.

TABLE 2.--Recommended road widths

Ground slope (percent)	Road width per following road lengths	
	100-300 m	300-600 m
	Meters	Meters
½ - 1	3	6
1 - 2	3	5
2 - 5	2	3
Above 5	1	2

Roads 6 m wide and over are used because of the limitations of available equipment and to enable a layer of subsoil to be obtained to blanket the road. The lower permeability that this usually has, at least in Western Australia, probably more than offsets the hydraulic disadvantages of the wider roads. In this context, the use of miniroads becomes very attractive, since they not only increase the yield, but also move the optimum width into the range currently in use. While the 0.5-m-wide ones being tried at present may increase the erosion risk on the side slopes, narrow ones of only 0.1 m could, in fact, reduce it by preventing the formation of normal rills with a tributary pattern. It thus appears that further work to develop techniques for forming miniroads would be most valuable.

Optimum Collecting Channel Design

Channel Cross Section Shape

The standard recommended collecting channel for roaded catchments is a trapezoid as shown in figure 2. This is used to prevent erosion by avoiding flow concentration, but, by the same token, it loses more water to infiltration. The V-channel shown in figure 2 has much lower losses and has the capacity to handle the outflow from substantial areas of catchment provided the gradient can be correctly designed to avoid erosion. It is, therefore, recommended that this type be used wherever possible.

In fact, the losses from the flat bed of the trapezoidal channel can be large enough to make it worth considering the use of a bed with a cross slope of at least 1 or 2 percent to provide some flow concentration when it is necessary to use the trapezoidal channel.

Maximum Channel Gradient

When the erosion hazard and ground slope are low, the design methods for maximum nonerosive gradients given above can result in grades equal to the ground slope for both the roads and collecting channel. Clearly, this is impossible, and ideally, both the road and collecting channel gradients should be reduced so that the runoff is maximized. However, this is impracticable as a routine procedure; it is necessary to use the design road gradient and then to adjust the channel gradient for minimum infiltration losses. Similar considerations restrict the maximum channel gradients for all road gradients. Figure 16 gives a curve for the optimum channel gradient for any given road gradient that was produced analytically and confirmed by model results.

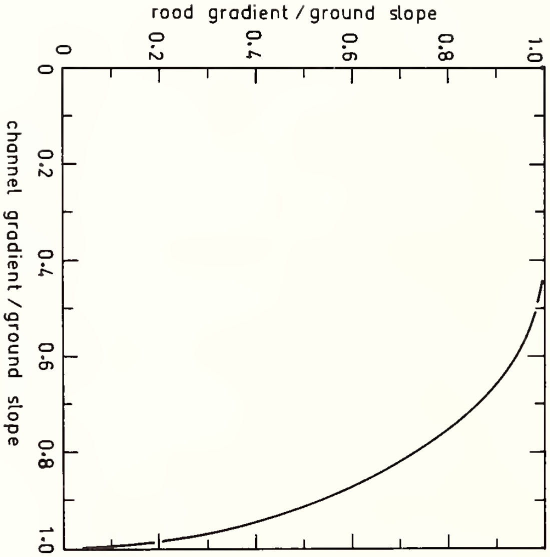


FIGURE 16.--Maximum channel gradient for any road gradient.

Optimum Road Length

The results given above for individual roads indicate that they should be as short as possible for maximum runoff; however, this is not the case when collecting channel losses are included. Figure 17 shows a typical plot of runoff percentage against road length for a range of catchment sizes and shows a distinct maximum with a more rapid drop on the short road side of the peak than on the long side. Also shown in figure 17 is a line of yields for "square" catchments in which the road length and road width times the number of roads are equal.

Results obtained suggest that an approximately square catchment layout is best where the channel gradient at the outlet end is steeper than that which would give a perpendicular intersection with the roads. However, as the gradients fall and the intersection angle becomes greater than 90°, the losses in the channel increase faster than those in the roads and the optimum shape moves towards longer roads.

Unfortunately, attempts to quantify this relationship have not been successful due to the interactions of other factors. Thus, the best recommendation that can be made is to use roads that are no shorter than

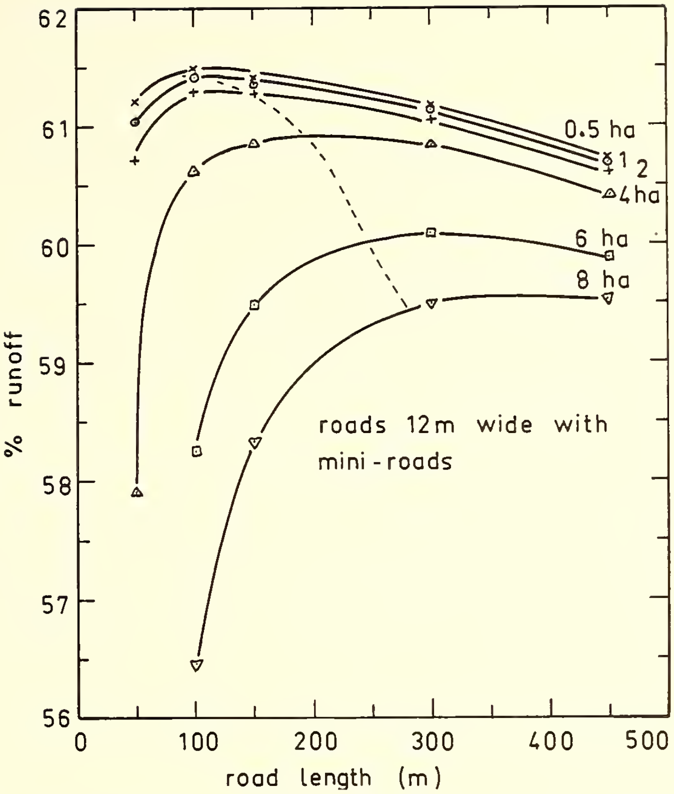


FIGURE 17.--Percent runoff versus road length for a range of catchment sizes.

would give a square layout when the outlet end of the collecting channel is steeper than for perpendicular intersection and as long roads as possible when this is not the case.

CONCLUSIONS

The attempt to produce a rational method for the design of road and channel gradients has not yet been entirely successful due to the difficulty of assessing the erosion resistance of soils. However, this is worth persevering with since the rules-of-thumb currently available are not completely satisfactory even in southwest Western Australia, and they are totally inapplicable to other parts of the world. Also, observations of existing catchments indicate that in many cases, with adequate design methods, it may be possible to use gradients that would cause most of the detritus that collects in the channels to be washed from the catchments. Since this detritus is one of the most serious causes of loss of effectiveness with time, this would be a big advantage.

It seems unlikely that the optimum road widths of 1 to 6 m will be accepted for most roaded catchments, because of the need for special equipment and the desirability of obtaining a subsoil blanket. However, experiments are presently being conducted in Western Australia to find suitable low cost surface treatments for reducing the infiltration rate into sandy soils (5), and the roaded catchment concept is being retained as complete impermeability is unlikely to be achieved. Narrow roads formed by a V-plow may have a place here.

The best prospects for improving the performance of roaded catchments seems to be in the development of techniques for forming miniroads. These not only increase the runoff, but give a wide range of acceptable widths that correspond well with those needed to allow the use of standard roadmaking equipment and to enable a subsoil blanket to be obtained.

Road lengths used in practice vary considerably according to the site, but generally already correspond quite well to the recommendations given here. Also, the V-collecting channel advocated for its concentration of the flow is frequently used by contractors, much to the annoyance of advisors to whom it is anathema!

While these changes will undoubtedly increase the effectiveness of the roaded catchment, it is impossible to say how large this effect will be. Among other things, the actual increase in runoff yield depends on the infiltration rate of the soil and the intensity/duration pattern of the rainfall.

ACKNOWLEDGMENTS

Thanks are due to the Department of Civil Engineering, University of Western Australia, for providing laboratory facilities; to the Western Australian Regional Computing Centre for computer time; and to the Gledden Trust and the Water Research Foundation of Australia for providing the finance to undertake this work. Particular thanks are due to the Australian Water Resources Council for making attendance at this Symposium possible.

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DISCUSSION

SESSION III, Part 2--Charles Staff, Chairman

H. VELASCO: What was the basis for the addition of the sodium polyphosphate as a chemical dispersing agent?

I. LAING: Soils responded to treatments of 0.1 percent sodium tripolyphosphate (STPP), reducing laboratory hydraulic conductivity. The soils are characteristically nondispersive but were dispersed after treatment with STPP. After STPP treatment in the laboratory, exchangeable sodium percentage was increased. At moisture contents near the plastic limit, the soils appeared more plastic following treatment with STPP.

R. REGINATO: What is the longevity of the STPP-treated stock tanks? Have you considered the use of sodium carbonate instead of STPP for sealing earth tanks?

I. LAING: The life of the STPP treatments has not been determined. More detailed investigations of the use of STPP is planned. The use of sodium carbonate has been considered and will be investigated in the future. At the time the investigations commenced, STPP was the chemical dispersant most commonly referred to in the literature.

H. BOUWER: What are the requirements of soil particle size of subgrade and cover to avoid pinholes in buried plastic membranes for reservoir linings?

A. DEDRICK: Information regarding the requirements is contained in ASAE Recommendation: ASAE R340, Installation of Flexible Membrane Linings. Basic to the use of thin film water barriers is proper subgrade preparation. If the subgrade is coarse textured or the materials are angular, a 1- to 2-inch layer of filter grade soil, type SW or finer (defined in ASTM D 2487), should be applied. If the cover material is also coarse, a thin cushion of soil should be applied to the lined area prior to covering. Standards for selecting the membrane thickness in relation to the soil subgrade are given in ASAE R340. Membrane thickness should not be increased to compensate for improper subgrade preparation.

M. McBRIDE: What effect does a tank that goes dry have on the wax? Does it blow away or get into the pipe and float valves?

K. COOLEY: The effect of an empty tank on the wax is not yet fully known. Studies are pursuing this problem. The wax has not given problems in float valves as it does not flow with the water.

I. LAING: What is the water temperature under the paraffin wax treatment?

K. COOLEY: For exposed wall tanks, the temperature of the water was higher under the wax cover by about 4° to 5° C. For buried tanks, the temperature stays slightly cooler, core nearly associated with the ground temperature at about one-half tank depth.

I. BRAZELL: Does the melted wax blow off the tanks during violent winds?

K. COOLEY: No. The melted wax, if applied to the tanks with 1 1/2 to 2 inches of freeboard, will stay in the tanks.

H. QASHU: Did you include sediment yield of particle detachment mechanisms in your analysis? If not, is it because you feel such effects are insignificant or because they involve a complex process?

M. HOLLICK: Erosion of the surface of the roads has not been studied. This can be a serious problem, particularly on the very wide clay blanketed ones now in use. The actual detachment mechanisms are too complex to model satisfactorily, but I hope eventually to evolve slope length/steepness guidelines related to the erosion resistance.

SESSION IV, Part 1--Richard Frevert, Chairman

WATER HARVESTING BY RUNOFF INDUCEMENT FOR IRRIGATION OF AN ALMOND ORCHARD IN A SEMIARID CLIMATE 1/

Ernest Rawitz and Daniel Hillel 2/

The success of runoff farming depends not only on the effective inducement and collection of runoff, but also upon efficient utilization of the water by agricultural crops. Since the uncertainties of runoff events are difficult to reconcile with crop requirements, it is crucial to choose the kind of crop that can make the best use of long term water storage in the soil. These considerations favor the selection of deeply rooted, perennial, drought-resistant crops, preferably trees (4). Almonds, which have been grown in this region since ancient times in runoff collecting fields, were chosen as an indicator crop since they meet the above requirements.

Various techniques found effective in increasing runoff from land surfaces, either singly or in combination, include land smoothing and compaction (4), formation of a sodic crust (2, 5, 6), and the spray-application of various asphaltic materials (5, 7, 8). Our previous experience has shown that while sodic crust are very effective in decreasing the infiltrability of loess soils, they are very vulnerable to erosion and thus short lived. Among various asphaltic formulations, heavy fuel oil diluted with kerosene proved to be both effective and economical (4).

Following the laboratory and field screening of various surface treatment methods, two promising treatments were chosen for a pilot-scale field experiment. A detailed description of the experiment as well as preliminary results were given by Rawitz (9).

EXPERIMENTAL CONDITIONS

The experiment was carried out in the semiarid northern Negev of Israel. Summers are long and hot; the winters, moderately cool. Rainfall averages about 225 mm annually, occurring very irregularly both from year to year and within the rainy season of November to April. The deep loessial soil has a sandy-loam texture, undeveloped structure and profile, with some secondary calcareous concretion deposits at about 150 cm. The soil tends to slake and crust upon wetting (3).

Experimental plots were laid out roughly on the contour on a natural slope having a grade of 4 or 5 percent. The trees were planted in a leveled basin at the bottom of water-contributing areas that were only lightly smoothed with a road grader (fig. 1). The entire contrib-

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1/ Contribution from the Faculty of Agriculture, Hebrew University of Jerusalem, Rehovot, Israel. This work was supported by the U.S. Department of Agriculture under the provisions of PL-480, and by the Central Research Fund of the Hebrew University.

2/ International Atomic Energy Agency expert, United Nations Development Program, New Delhi, India, and Professor and Head, Department of Soil and Water Sciences, Hebrew University, Jerusalem, Israel.

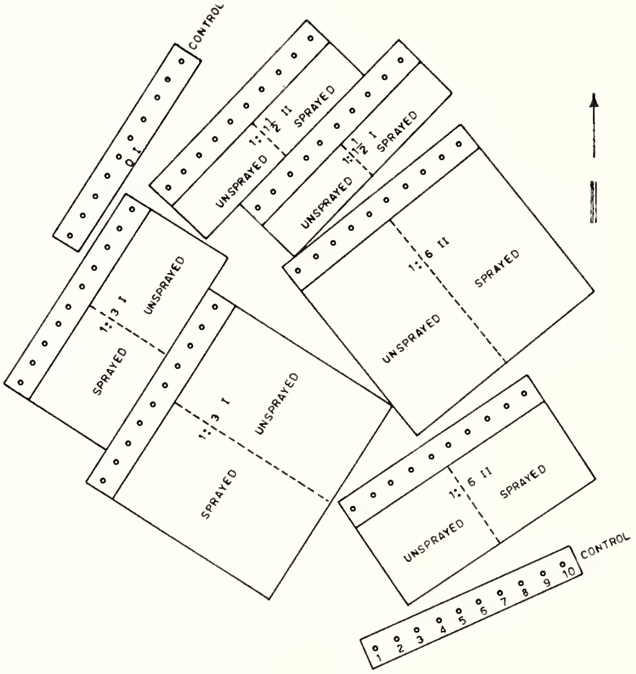

FIGURE 1.--Layout of Gilat runoff orchard (Source: 9).

uting area was also compacted after the first fall rain with a vibrating sidewalk roller. In addition to the control plot of trees that had no water-contributing area, main treatments consisted of contributing areas 1 1/2, 3, and 6 times as large as the 4 by 40 m receiving basins. The trees were planted in the winter of 1966, receiving supplementary irrigation during their first summer. One half of each contributing area was sprayed in 1968 with 200 liters of fuel oil per 1,000 m^2, followed by a respraying at approximately half the above rate every 2 years after this. In our previous study (4), it was found that the surface treatment deteriorates after about 2 years, while supplementary spraying maintains, and even enhances treatment performance.

During 1968 and 1969, soil water content was determined gravimetrically at the end of the rainy season in the spring, and root zone water storage so determined served as an index of runoff yield and crop-available water. Neutron-probe access tubes were installed midway between two trees in all the plots in the winter of 1970, and regular readings were taken both during the rainy season and the growing season. Crop response was characterized mainly on the basis of weight per tree of unshelled almonds after removal of the outer green shell. Weight per 100 almonds, weight of shelled almonds, and fruit size were also determined.

RESULTS AND DISCUSSION

The data for 1972 were not available during preparation of our previous report (9), and the trees had not reached the maturity required for commercial yields. The tentative conclusions drawn at the time will therefore be examined in the light of the more normal yield of 1972. A summary of growing conditions and yields is given in table 1. It is seen that the size of the water-contributing area had a pronounced effect on the yield of the main treatments, and that the yields also reflect seasonal precipitation. However, the effect of surface treatment is less pronounced, and its magnitude is to some extent dependent on the amount of rainfall, as well as on the developmental stage of the trees. There are a number of instances where the sprayed treatment was inferior to the merely compacted one, and this may be attributed to the natural annual variability of fruit trees, as well as to the soil variability and imperfections in leveling, which lead to uneven distribution of water in the soil and thus, possibly, to unrepresentative soil moisture data. A more consistent pattern is obtained if one considers the average of several seasons. On this basis, it becomes evident that the sprayed treatment was superior to the compacted treatment, as is shown in figure 2. Both this figure and figure 3, which shows composite yields of sprayed and compacted treatments by years, confirm some of the observations of the preliminary report. In general, there appears to be an optimum contributing area of about 50 m^2, and this optimum may shift depending on seasonal rainfall pattern and amount and on the extent of the root zone. Thus, the 1972 season was both the wettest of the 4 years, and the trees were older and presumably had a better developed root system. It is therefore expectable that the optimum area of contribution would be smaller. There is also some indication of a threshold below which the contributing area is relatively less effective, especially in drier years. This is due to the lower runoff coefficient associated with small rains, as well as with greater evaporation losses from the soil

TABLE 1.--Summary of growing conditions and yields, 1969-72

Area ratio	0	1 : 1 1/2		1 : 3		1 : 6	
Surface treatment	None	Sprayed	Compacted	Sprayed	Compacted	Sprayed	Compacted
Contributing area, m^2/tree	0	24	24	48	48	96	96
Year and rainfall (mm)	Yields, grams per tree of unshelled almonds						
1969 204 mm	103	376	146	208	201	394	218
1970 95 mm	10	10	34	132	198	202	206
1971 220 mm	140	225	169	345	291	336	327
1972 300 mm	1,103	2,325	1,981	2,547	2,018	2,220	2,107
Average yield, 1969-71	84	204	116	228	230	311	250
Average yield, 1969-72	340	733	583	808	678	788	714

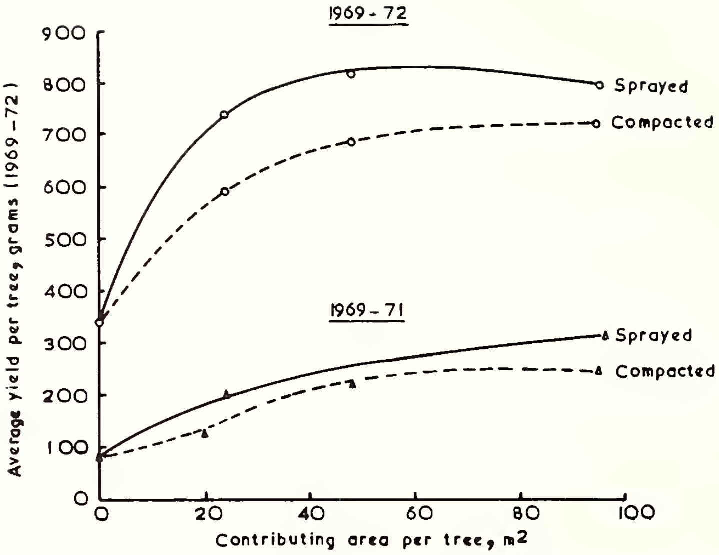

FIGURE 2.--Relation between yield of unshelled almonds and size of water-contributing area.

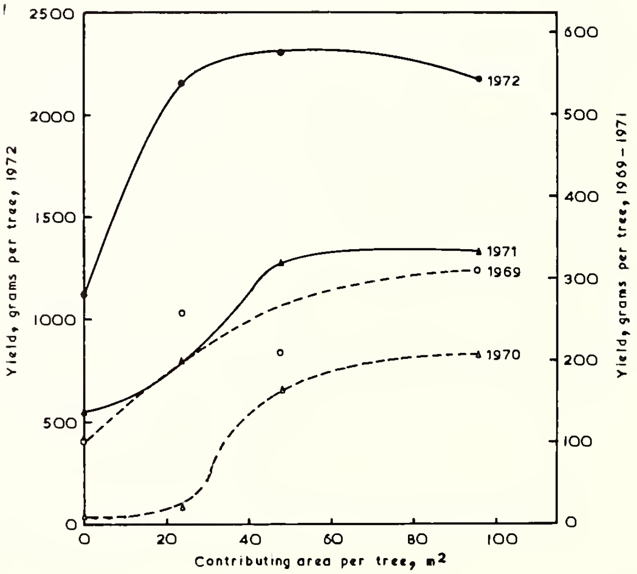

FIGURE 3.--Almond yield response to size of water-contributing area (composite of surface treatments).

in the infiltration plots where the smaller amount of runoff penetrates only to a shallow depth.

The average weight of almonds as a function of contributing area is shown in figure 4. In spite of the very large range of yields, the size of fruit varied much less than yield with contributing area, especially when yields were relatively high. Yield differences are therefore attributable mainly to the number of fruit per tree, while fruit size remains relatively unaffected by environmental factors. The number of fruit surviving to maturity is apparently determined by a mechanism sensitive to water available for yield production. This may be related to fruit set (determined early in the spring when soil water storage is at its maximum), or more likely, to fruit drop when water stress begins to affect the tree. In addition, flowering and fruit set may also reflect the previous year's growing conditions.

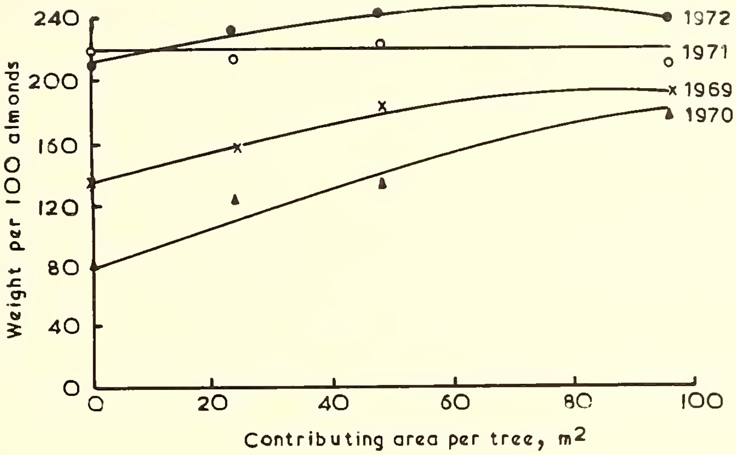

FIGURE 4.--Relation between weight of 100 almonds and contributing area.

Up to this point, results have been interpreted on the implicit assumption that there exists a more or less linear correlation between contributing area and usable water yield, due to the unavailability of continuous soil moisture data for the first two and a half seasons. That this assumption is incorrect is shown in figure 5. It is known in hydrology that size of watershed affects the runoff coeffiecient (1); in addition, in a wet year some of the water may penetrate below the root zone and not be accounted for either by soil sampling or, for that matter, by plant uptake. Nevertheless, analysis on the basis of relation between receiving and contributing area has its practical usefulness for design purposes in a particular area and soil type. A more fundamental approach must be used, however, to gain an understanding of the processes involved (10).

In order to obtain at least some information on soil moisture status, gravimetric samples were extracted at the end of the rainy seasons of 1969 through 1971, and the amount of water stored above the presumed "Permanent Wilting Percentage" of 7.5 percent by weight was taken as an index of available water for the coming growing season. These data were also used to construct figure 5. For the 3 years in question, there was a roughly linear relation between yield and soil water storage (fig. 6), but for 1972 there was only a difference between the driest treatment and all the rest. This is reasonable, since figure 5 also shows that the wetter treatments had approximately equal water storage at that time.

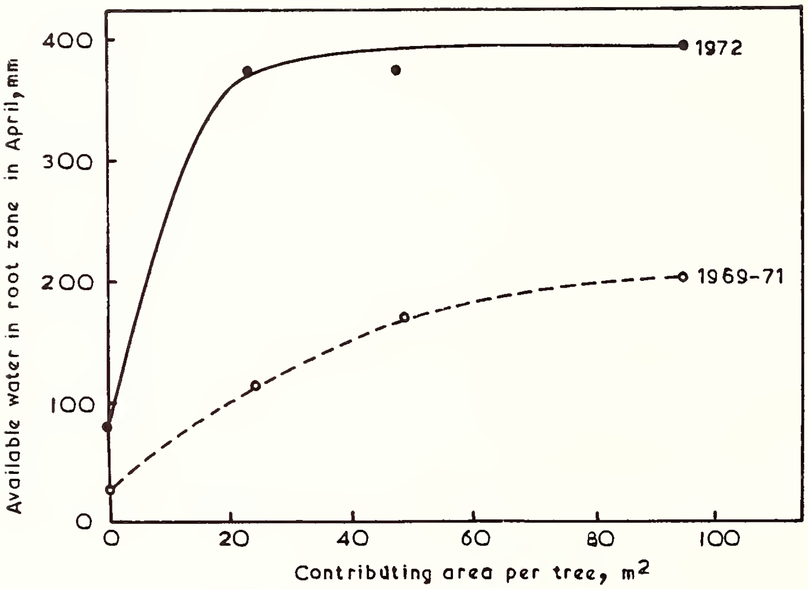

FIGURE 5.--Root zone available water storage at start of growing season as a function of contributing area.

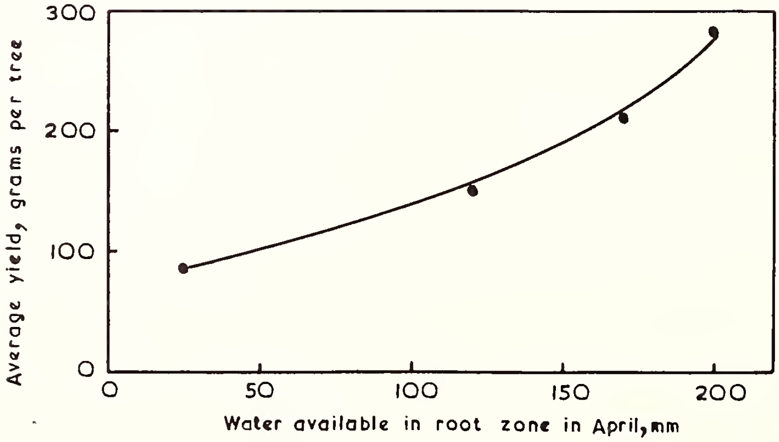

FIGURE 6.--Average almond yield (1969-71) as function of available water stored at 210 cm in root zone.

Continuous soil moisture monitoring by neutron probe began in February 1971, by which time more than half the seasonal rain had fallen and large differences in moisture storage between treatments were evident. The record of "available" water for the two seasons is shown in figures 7 and 8.

The record for 1972 shows different initial storage amounts for the various treatments, and not in conformity with the treatment sequence. This could be due either to variability in soil properties or to non-uniform water distribution. Other apparent anomalies appeared during the season, so that at the end of the season recorded storage also did not conform to the expected pattern. Plant response was thus interpreted on the basis of water depleted from the root zone rather than on the basis of water content at any one time. The depletion rate can not be equated with evapotranspiration, since a certain amount was no doubt lost by deep drainage. The rate of depletion decreases with soil water content, which is consistent with current theories of soil water availability to plants was well as with the laws of unsaturated flow. In both years, there is a pronounced decrease in depletion rate at about 13 percent water content by weight, which is equivalent to about the one-bar tension.

For the short period of record in 1971, yield was correlated with total recorded water depletion; for 1972, only the amount depleted from the beginning of active growth at the end of March to the harvest date was used. It is assumed that earlier depletion took place either by deep drainage or evaporation from the soil surface, as the trees were dormant. The relation between yield and water depletion is shown in figure 9. There seems to be a slight advantage to the sprayed plots in

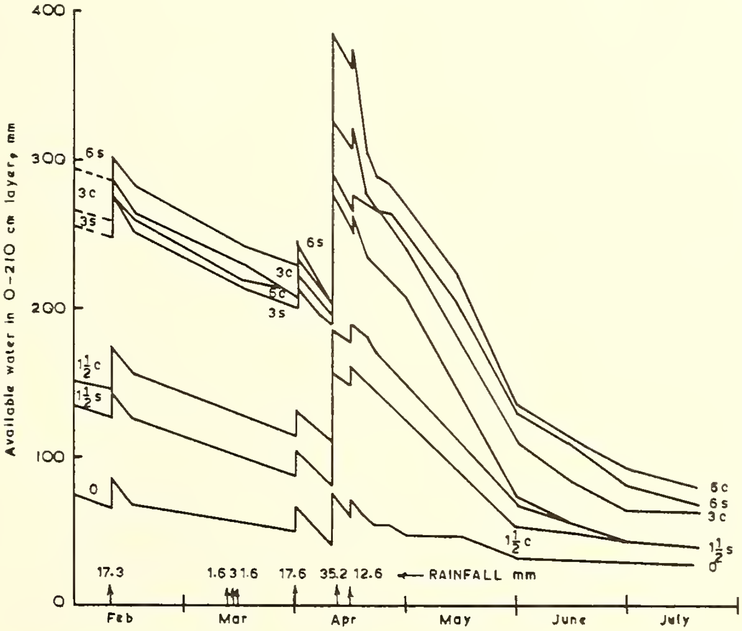

FIGURE 7.--Available water storage in root zone, February to July 1971. (Source: 9)

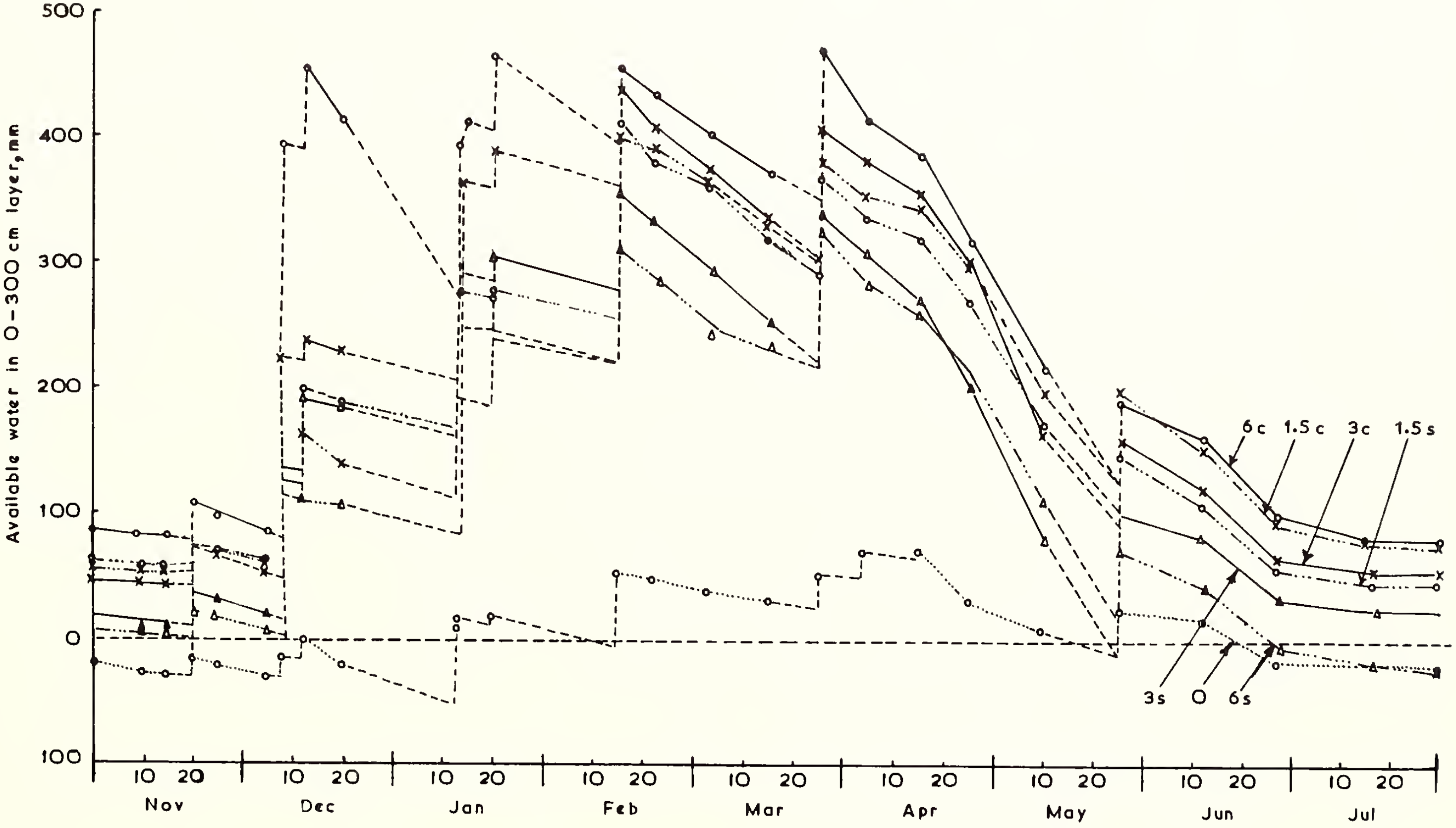

FIGURE 8.--Available water storage in root zone, 1972 season.

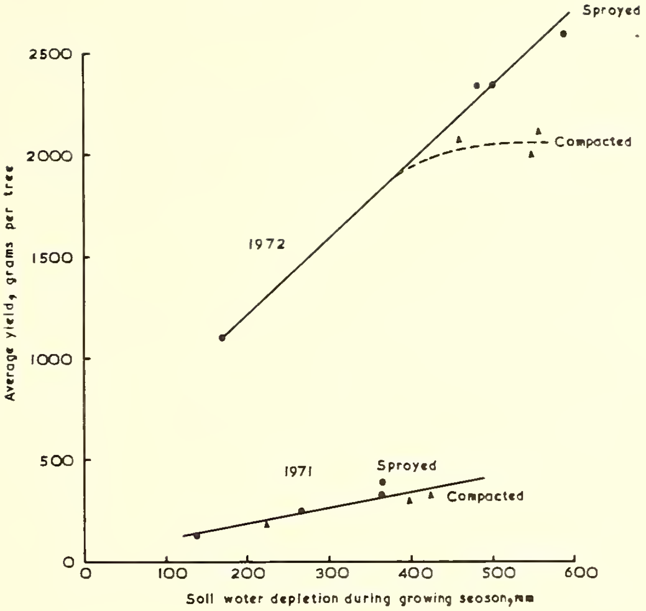

FIGURE 9.--Relation between yield and water depleted from the root zone (Feb. to Aug. 1971, 0-210 cm; Mar. to Aug. 1972, 0-300 cm).

both years, though the reason for this is not clear. It was expected that yield would be a single function of water use or availability, regardless of how this water entered the soil.

While the results of this experiment leave open a number of questions relating to the best topographical arrangement of runoff farming plots, engineering solutions for problems of land shaping and water conveyance, as well as the economics of runoff-farming, they do show that runoff-farming is possible in this 200 to 250 mm rainfall area. Area ratios between contributing and receiving areas on the order of 3:1 to 6:1 provide seasonal accretion in a deep soil profile of well over 600 mm, and it appears that in rainy years part of the contributed runoff water penetrates to below the rooting depth. The accretion achieved provides soil moisture equivalent to the entire normal winter rainfall in the Mediterranean climatic zone, which includes much of central and northern Israel, where unirrigated orchards provide a livelihood for an appreciable number of farmers.

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FIELD EVALUATION OF MICROWATERSHED AND VERTICAL MULCH SYSTEMS

Merle L. Fairbourn 1/

INTRODUCTION

An estimate has been made that more than 60 percent of the precipitation that falls on the semiarid Great Plains is lost by evaporation (5). The objective of a microwatershed cropping system is to redistribute precipitation to small crop areas where the water is concentrated, resulting in deeper infiltration into the soil. Thus, cumulative evaporation with time is reduced (4), and the soil water available for plant use is increased.

Kemper 2/ applied the microwatershed crop system at Fort Collins, Colo., to determine if water use efficiency by crops was increased. His treatments (fig. 1) included a uniformly spaced, flat surface control and uniformly spaced rows on a ridged surface. He also included two treatments with double rows, having slope-to-crop area ratios of 3 to 1 and 4 to 1. His yield (table 1) did not consistently favor any

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1/ Soil scientist, Agricultural Research Service, U.S. Department of Agriculture, Fort Collins, Colo.

2/ Kemper, W. D. Unpublished research data from annual Agricultural Research Service reports.

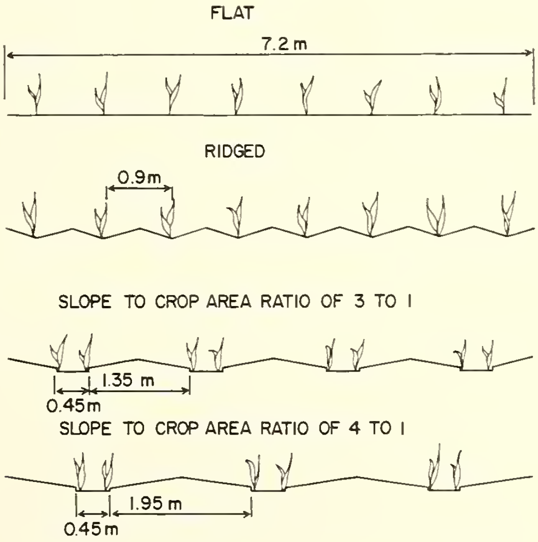
FLAT
7.2 m
RIDGED
0.9m
SLOPE TO CROP AREA RATIO OF 3 TO 1
1.35 m
0.45m
SLOPE TO CROP AREA RATIO OF 4 TO 1
1.95 m
0.45m

FIGURE 1.--Treatment design (courtesy W. D. Kemper).

TABLE 1.--Treatments and plant population, precipitation, and corn grain yields for 5 consecutive years 1/

Year	Annual Precipitation	Treatments and plant population			
		Flat 42,500	Ridged 42,500	3 to 1 42,500	4 to 1 32,500
	Cm	Kg/ha	Kg/ha	Kg/ha	Kg/ha
1964	13.8	230	426	---	---
1965	32.3	3,182	4,257	3,691	2,545
1966	13.9	465	343	320	739
1967	42.5	4,619	2,952	3,933	2,711
1968	24.3	808	---	1,349	1,877
Average yields		1,861	1,994	2,323	1,968

1/ Courtesy of W. D. Kemper.

one treatment, although average production for the microwatersheds was increased compared with the control. Yield differences did not appear to have a very high level of significance. Thus, the real worth of these microwatersheds for storing soil water and using it efficiently appeared questionable from an economic viewpoint.

Modification of Kemper's microwatersheds for improvement of water use efficiency appeared possible. A comparison of Fort Collins precipitation data with the yields of table 1 indicated that the efficiency of the microwatershed system for storing soil water depends upon size and intensity of precipitation events; also, a 3-to-1 ratio of contributing slopes to crop area seemed most nearly suited to the clay or silt loam soils and precipitation of eastern Colorado. In a previously reported laboratory experiment (3), observation was made that by using a vertical mulch in the crop area water could be infiltrated deeper into the plant root zone. Compared with a nonmulched crop area, 10 percent more of the added water was saved. Calculation was made that if the contributing slopes were sealed so they would cause 90 percent of the precipitation to run off, the savings of added water with time would be increased from the observed 10 percent to approximately 25 percent. This paper reports a field experiment to evaluate a 3-to-1 microwatershed treatment with vertical mulch in the crop area and hydrophobic treated contributing slopes.

PROCEDURE

The research was conducted on a Rago silt loam at the Central Great Plains Field Station, Akron, Colo. Average annual precipitation at the station is 40.0 cm.

Three main treatments (fig. 2), vertical mulched microwatershed, nonmulched microwatershed, and a flat surface control, were replicated twice on both cropped and fallowed plots. Thus, there were 12 plots (8.0 by 15.0 m) on a split plot layout since all plots for a treatment were alined due to the design of the treatments. Each plot had four sets of double rows, and all soil water and plant harvest sampling was

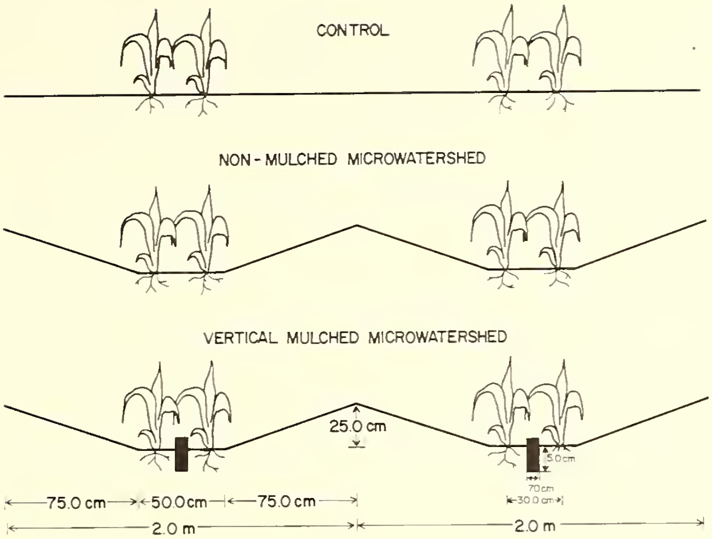

FIGURE 2.--Treatment design and row spacing.

done from the area of the two center sets. Each microwatershed treatment consisted of a 75-cm contributing slope flanking each side of a 50-cm-wide crop area (row area). Hence, the ratio of contributing slopes to row area was 3 to 1. The ridges between row areas were 2 m apart. Wheels of all equipment were adjusted to run on the ridges for such operations as planting and harvesting.

The microwatersheds were constructed in November of 1971 with an hourglass-shaped roller mounted in a steel frame. Two scraper blades mounted ahead of the roller ridged the soil to the center where it was rolled into a broad, A-shaped form. The ridge was further compacted and smoothed by pulling a heavy roller along one slope at a time. The contributing slopes were treated with a hydrophobic compound, Armosoft AR-40, a product of Armour and Company (1). Application rate was 0.25 percent active ingredient of the hydrophobe based on air-dry soil weight of approximately 36,800 g for the top 2.5-cm depth of each square meter of surface area. Each square meter of the treated slopes required 92 g of Armosoft (active ingredient) and 5 liters of water. Since Armosoft AR-40 is 40 percent active ingredient, the total hydrophobic material used was 230 g/m^2. The hydrophobe mixed readily into solution when the water was heated to 120° F. The mixture was applied as a spray, and the top 2.5 cm of soil was successfully wetted.

A small trenching machine was used to construct a vertical mulch trench 7 cm wide and 15 cm deep. Bales of sudangrass were cut in half with a chain saw through the length of the bale, and small sections of the baled grass were hand placed end to end to give a continuous mulch through the length of the trench. Approximately 5 cm of the mulch protruded above the soil surface to keep the infiltration route open throughout the crop season. Mulch material was applied at the rate of 7 metric tons per hectare.

Small earth fills extending from ridge to ridge across the row areas served as check dams. These were placed at 15-m intervals in 1972 and 7.5-m intervals in 1973.

Soil water content was determined as early each spring as it was possible to get into the field and at 2-week intervals thereafter throughout each growing season. Measurements were obtained (1) on each microwatershed plot from the center of row areas and also contributing slopes and (2) on each control plot from the center of row areas and also between sets of double rows. Hence, there were two sampling locations for each plot. Depths of samples were referenced to the top of the profile in each sampling location. Sampling depth was 180 cm, except at the start and end of each season, when the depth was 300 or 360 cm. Soil water content was determined by gravimetric analysis and converted to percent water by volume in 1972, but the neutron method was used in 1973.

Water harvest efficiency was measured in the field for both treated and untreated slopes. However, these measurements were obtained from microwatersheds separate from but near to the plots described above. Water catchment areas (60 by 75 cm) on the microwatershed slopes were enclosed with metal edging and the runoff from these areas was funneled into storage containers. These were placed below the soil surface inside a large diameter covered metal can and could be removed for measuring and emptying the water after each precipitation event. Collected runoff was compared with potential runoff from the catchment areas to determine water harvest efficiency.

Crop plots were fertilized ahead of sorghum planting, and both crop and fallow plots were treated with a preemergent application of atrazine for weed control. The fertilizer required for each plot was based on soil test recommendations for the total plot area but was applied to only the row areas. Nebraska 505 sorghum was planted at the rate of 4.5 kg/ha, which gave a population of approximately 70,000 plants. Planting was done on June 12, 1972, and June 18, 1973. The herbicide was applied to the total surface area of plots. A moderate amount of hand weeding was also required for resistant species.

Harvest samples were obtained by random selection of 1.2-m lengths of rows on each plot. Yield determinations were based on entire plot area and not just row areas.

RESULTS AND DISCUSSION

Water infiltrated the soil readily on the vertical mulched microwatershed treatment. Approximately 24 hours after a 1.5-cm high intensity rain, the surface soil of the vertical mulched microwatershed treatment was nearly all dry. In contrast, the total row area of the nonmulched treatment was wet. This also demonstrated the purpose of the check dams. They kept the water from running off the microwatershed plots. Much of this high intensity rain was lost through runoff from the control treatment. Compared with the wet soil surface of the nonmulched microwatershed row areas, the control treatment appeared dry at this time.

Depth of water infiltration caused a marked difference in soil water storage on the treatments (fig. 3). The precipitation of 1972 was near average in amount and distribution. Many of the individual precipitation events were of sufficient size and intensity to produce runoff except during the winter months. Since the soil had low water content following the previous crop, one of the objectives of fall installation of the microwatersheds was to increase soil water during the winter season. The winter precipitation produced very little runoff, and row area water content profiles were very similar for all crop plots on the first sampling date of April 18 (fig. 4). Soil water storage during the spring and summer seasons of 1972 was greatly

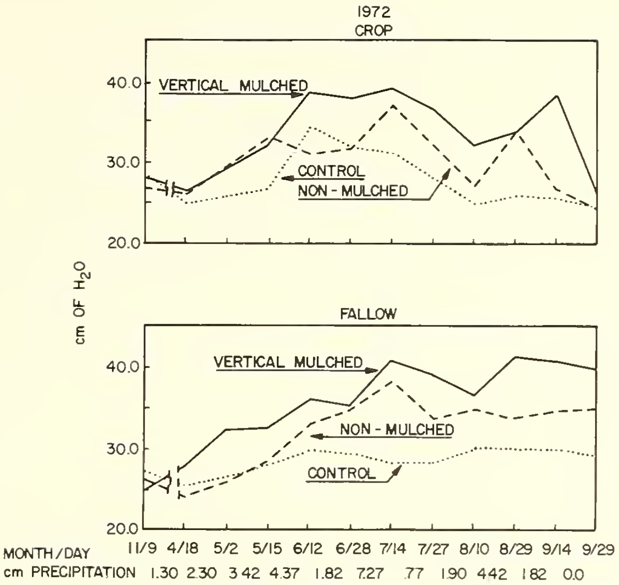

FIGURE 3.--Water in 180 cm of the row area soil profile for crop and fallow treatments with sampling dates and precipitation during 1972.

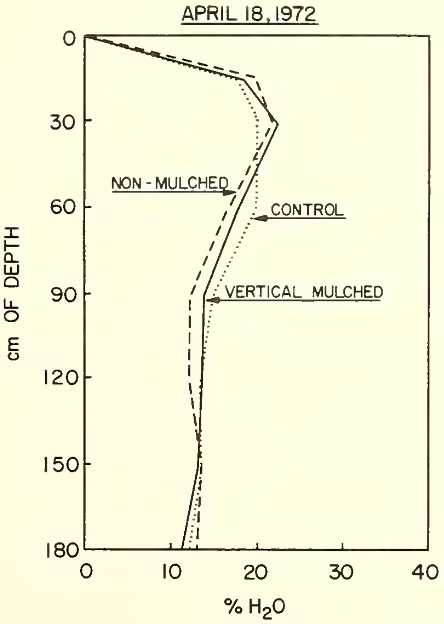

FIGURE 4.--Volumetric water content versus depth under row area for crop treatment on April 18, 1972.

increased on the vertical mulched treatment, and deep water infiltration was of major influence. This was shown by a comparison of the row area water content profiles on June 12 (fig. 5) with those of April 17 (fig. 4). The water content shown for the vertical mulch crop treatment on June 12 appeared to be near a peak storage for the season (figs. 2 and 4). However, this storage level appeared to have been reached again in July and September. The soil water storage on the crop control treatment near planting time was high compared with the fallow control and the nonmulched microwatersheds. This was due to tillage on the crop control plots at this period, which increased water infiltration into the soil. The infiltration advantage was lost once the soil became crusted.

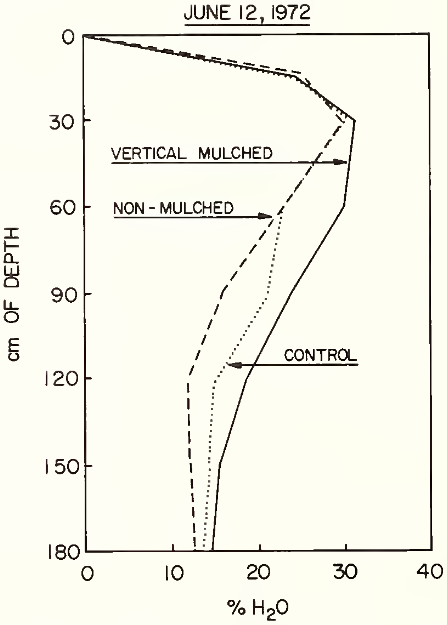

FIGURE 5.--Volumetric water content versus depth under row area for crop treatments on June 12, 1972.

The difference between crop and fallow treatments on final soil water storage in 1972 points up the high water demand of sorghum plants during the period from heading to maturity. Research has shown that yields of grain sorghum have a high correlation with water during this critical period [3] (2, 6). Hence, the soil water data for 1972 indicated a high yield potential throughout the season for the vertical mulch treatment but a low potential for the control. The row area water content profiles of September 29 (fig. 6) showed that the control crop was unable to use the late season water to the same extent as the plants on other treatments. This was probably due to a high percentage of senescent leaves on the plants of this treatment in late August.

Water content in the crop treatment soil profiles showed a sharp contrast between the harvest date of September 29, 1972 (fig. 6), and

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[3] Lazo, Evaristo. Effects of timing and sequence of plant moisture stress on grain sorghum. M.S. Thesis, Iowa State University of Science and Technology, Ames, Iowa. 1969.

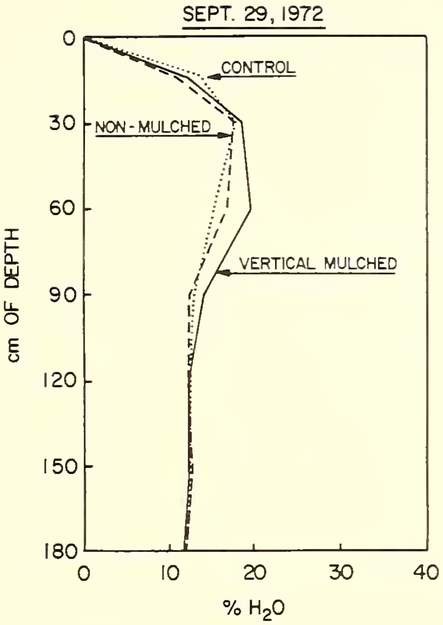

FIGURE 6.--Volumetric water content versus depth under row area for crop treatments on September 29, 1972.

the field entry date of May 29, 1973 (fig. 7). The high precipitation during this period was a 10- to 12-year frequency occurence 4/. Sampling to the 360-cm depth on May 29 did not reveal a wetting front on any of the treatments except the noncrop control where soil water storage was relatively low (fig. 8). This treatment was generally windswept of snow throughout the winter, whereas the stubble on the crop control plots was drifted full of show in early October and again with each succeeding snow event. Snowmelt ran into the soil throughout the winter on the crop, but not on the fallow control plots. Stubble from the 1972 crop served as a mulch and appeared to reduce runoff and evaporation from the crop control plots. Thus, the fallow control was at a disadvantage in over winter soil water storage compared with all other treatments.

Soil water storage for the crop season of 1973 was very different compared with that of 1972. The data (fig. 8) show that the season began with the soil profile filled with water on all crop treatments. The precipitation events for June, July, and August were generally 0.5 to 1.0 cm in size and produced little runoff from the microwatersheds. Hence, none of the treatments showed much soil water increase until September 11, when a 2.5-cm high intensity rain was received. Deep infiltration on the vertical mulch treatment gave it an advantage in soil water storage over other treatments. However, this soil water storage data for 1973 indicated that grain sorghum yield potential was relatively high for all treatments (2, 6).

The Armosoft treatment, on slopes of the microwatersheds, did not appear to be of much influence on soil water storage. The hydrophobic compound caused a harvest efficiency of 65 percent compared with 50 percent for a nontreated slope. Thus, the objective of 90 percent

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4/ Precipitation data for Akron, Colo.

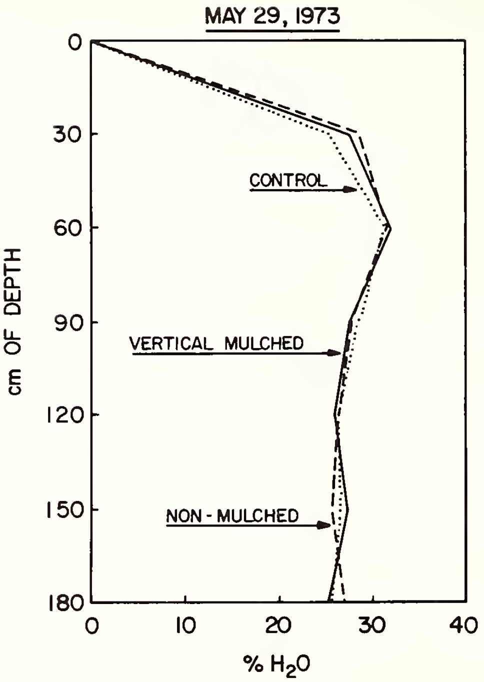

FIGURE 7.- Volumetric water content versus depth under row area for crop treatments on May 29, 1973.

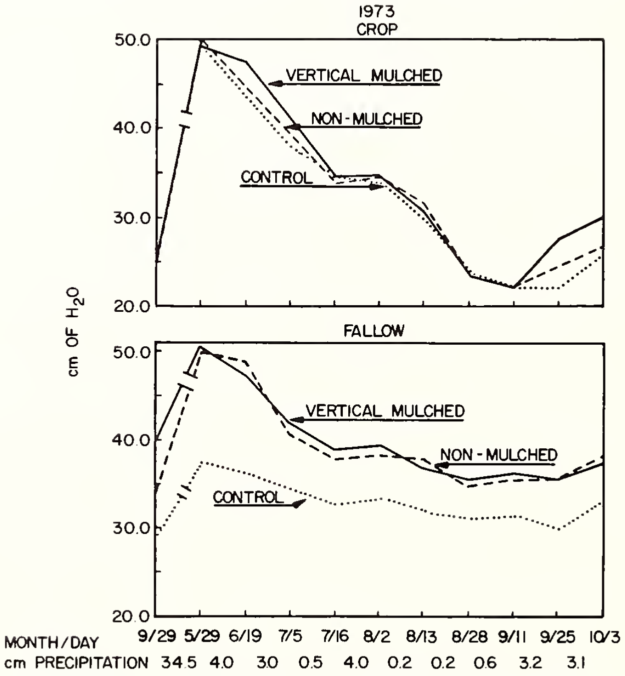

FIGURE 8.--Water in 180 cm of the row area soil profile for crop and fallow treatments with sampling dates and precipitation during 1973.

runoff from microwatershed slopes was not achieved and appeared to be nonessential for Rago silt loam and the precipitation of the Akron area.

Soil water used to produce a crop was assumed to be of uniform depth over the total treatment area. Therefore, it was necessary to average the profile water content values of all sampling locations for a treatment. The water content measurements showed that plant roots used water not only from the row areas but also from under the contributing slopes of the microwatersheds and from between the sets of double rows on the control plots. The difference between average soil water content of a treatment at the beginning and end of the crop season was added to the precipitation for that period to determine the total water used (table 2). The water used on fallow plots in 1972 generally represents the amounts lost by evaporation and/or runoff. The control treatment lost all the precipitation both years plus 0.6 cm of stored water in 1972 and 3 cm in 1973. The difference of 4.5 cm between the control and the nonmulched microwatershed treatment in 1972 was assumed to be the amount of water lost by runoff from the control treatment. This also appeared to be the amount of water saved by check dams on the microwatershed treatments. The difference of 2.4 cm between nonmulched and vertical mulched microwatersheds in 1972 represents the water saved in the soil through deep infiltration, which reduces evaporation loss with time (3, 4). The water used in 1973 on both fallow microwatershed treatments included loss through deep drainage in addition to evaporation. The deep drainage loss was negligible in 1972.

TABLE 2.--Treatments, water use, and precipitation for 1972 and 1973

Treatment	1972		1973	
	H_2O used	Grain	H_2O used	Grain
	Cm	Kg/ha/cm	Cm	Kg/ha/cm
Fallow				
Vertical mulched	11.5	--	25.2	--
Nonmulched	14.4	--	22.5	--
Control	18.9	--	18.2	--
Crop				
Vertical mulched	29.3	160.3	34.0	121.0
Nonmulched	24.9	154.8	32.6	90.4
Control	28.5	65.7	30.3	98.7
Precipitation	18.3	--	15.2	--

No attempt was made to determine water use components on the crop plots due to the complication caused by adding plants to the system. Therefore, each treatment production, per hectare per centimeter of water, was determined by dividing the total water used into the grain yield. The vertical mulch treatment showed a consistent advantage in water use efficiency. The 2-year average grain production on this treatment, for each hectare per centimeter of water used, was 140.6 kg. Comparable values for the control treatment of this experiment and Shawcroft's 5/ conventional planting with 1.0-m row spacing were 82.2

5/ Shawcroft, R. W. Unpublished research data in Agr. Res. Serv. annual reports from Akron, Colo.

and 67.6 kg, respectively. Thus, the vertical mulch microwatershed increased water use efficiency by 58.4 and 73.0 kg/ha-cm, respectively, over the control treatment and conventional tillage at Akron. Smika [6] obtained a 61.1 kg/ha-cm increase in water use efficiency at North Platte, Nebr., where he compared chemical fallow to conventional tillage practices for sorghum production. His work indicated that, from an economical viewpoint, the vertical mulch microwatershed system might have less appeal in high precipitation regions than other water conserving methods such as chemical fallow. However, where precipitation events occur mainly as high intensity thunderstorms in arid or semiarid regions or where soils are slowly permeable to water, the vertical mulch microwatershed system has high potential for increasing water use efficiency.

Soil water storage undoubtedly was the major factor that caused increased yields on the vertical mulched microwatershed compared with other treatments (table 3). The yield increase was 22 percent in 1972 and 40 percent in 1973 above the nonmulched microwatershed treatment. Comparative figures were 150 percent and 37 percent above the control treatment. The data show the vertical mulch modification to Kemper's 3-to-1 ratio microwatershed treatment had a tendency to stabilize yields at Akron, whereas the nonmulched and control treatments were more variable depending on the amount and distribution of precipitation.

TABLE 3.--Treatments and yields of grain sorghum for 1972 and 1973

Treatment	Yield 1/ 1972	Yield 1/ 1973
	Kg/ha	Kg/ha
Vertical mulched microwatershed	4,698a	4,114a
Nonmulched microwatershed	3,856b	2,947b
Control	1,874c	2,993b

1/ Values followed by the same letter for a given year are not significant at the 5-percent level.

CONCLUSIONS

1. A microwatershed system with a contributing slope to crop area ratio of 3 to 1, as designed for this experiment, appeared to be suitable for the soil type and precipitation at Akron.

2. Sealing the contributing slopes did not cause enough water saving on Rago silt loam to justify the expense and labor for treatment. This conclusion does not necessarily apply to other soil types or the precipitation at other locations.

3. Check dams were highly important for water storage on the microwatershed system since they prevented runoff from the plot areas. They saved 25 percent of the added water compared with the control treatment in 1972.

4. The vertical mulch with check dams infiltrated water deeper

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[6] Smika, D. E. Unpublished research data in Agr. Res. Serv. annual reports from North Platte, Nebr.

into the plant root zone and caused 16 percent saving of added water compared with the nonmulched microwatershed; 41 percent saving compared with the control treatment. This water saving potential on the vertical mulched microwatersheds with check dams indicated this system could be very useful in areas where most rainfall comes as high intensity thunderstorms and on soils that have slow water permeability.

5. Water saved on the vertical mulched treatment appeared to cause an increase in yields ranging from 37 to 150 percent compared with the control treatment. Hence, vertical mulched microwatersheds seem to have the potential for increasing and stabilizing annual yields in semiarid regions.

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AN ANALYSIS OF THE EFFICIENCY OF MICROWATERSHED SYSTEMS

H. R. Gardner [1]

INTRODUCTION

The soil water diffusivity equation predicts that if the amount of water infiltrated into the soil is increased, the evaporation loss, after a given time, is also increased, but by a lesser amount. Thus, if water could be moved deeper into the soil, the percentage of the added water that is lost by evaporation in any given time would be decreased. One way to get water deeper into the soil is to put more water on the soil surface and keep it from running off since water infiltrated into the soil percolates to a depth that is a function of the water content and the soil properties. Under nonirrigated conditions, the total amount of water is limited; thus, the only way to get more water for deeper penetration is to concentrate the rainfall received on the soil surface by moving it from one surface location to another.

The principle of concentrating the water was applied in the farming system being examined in this paper. A runoff collection area of one or more rows of crop is flanked on each side by a small runoff area. When this system is repeated across a field, the runoff slopes form ridges between the catchment or runon areas that are parallel to the crop rows. The runoff slopes and runon areas can be varied in width to change the water collection characteristics. The maximum width of runon area must be consistent with the water spreading characteristics of the area and with farm equipment that would be used. The soil surface roughness limits the width that water will spread. The length of the slope must be consistent with the amount of surface erosion that is caused by runoff water. In addition, the longer the slope, the deeper the cuts necessary to obtain soil to form the ridges. The amount of soil to be moved could become critical if it were great enough that special heavy equipment were necessary.

The optimum water storage of a runoff farming system requires 100 percent runoff and placement of the water on a catchment area that is narrow enough so that the water will spread across the entire area but will not allow penetration of the water to a depth below the plant root zone. Obviously, since the requirements for the optimum system would change for each rain, a seasonal optimum would be necessary. The condition for maximum water storage would require that the entire field consist of runoff slopes with 100 percent runoff and essentially no runon areas at the bottom of the slopes. Plants would be grown in a row at the bottom of the slope. The microwatershed system discussed in this paper follows the above concept as far as is practical.

DESCRIPTION OF RUNOFF PLOTS

The data used in this paper were obtained from plots on Rago silt loam at the Central Great Plains Field Station at Akron, Colo. The plot treatments consisted of an untreated check, which was tilled only enough to control weeds; a microwatershed treatment; and a microwatershed with vertical mulch treatment. Each treatment was replicated twice on plots measuring 8 m by 15 m. Figure 1A shows the cross section of the microwatershed system used. A total width of 2 m from peak to peak for the microwatersheds was chosen so that the wheels of farming equipment could be run on the tops of the ridges. The height from bottom to top of the ridge was 25 cm. If plants are grown in two rows, 50 cm apart, in the bottom area between ridges, then the average row spacing and plant population would be the same as those normally used in the dryland area of Colorado.

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[1] Soil scientist, Agricultural Research Service, U.S. Department of Agriculture, Fort Collins, Colo.

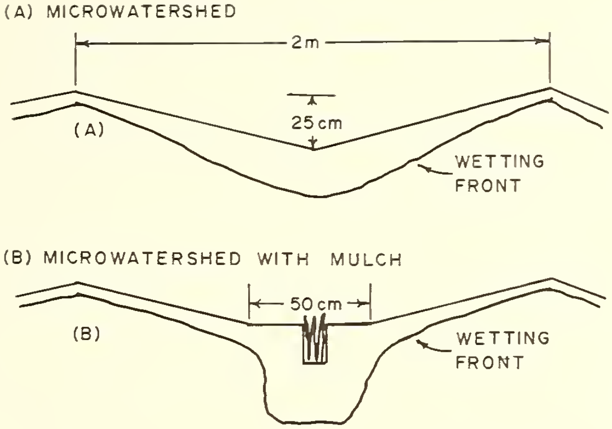

FIGURE 1.--Cross sections of a microwatershed system with a wetting front from a hypothetical small rain. Cross section A is without vertical mulch. Cross section B is with vertical mulch.

According to Fairbourn and Gardner (1) the water for the microwatershed system with minimum runon area, when ponded between slopes, infiltrates horizontally as well as vertically, which tends to counteract the concentrating effect. When this happens, the evaporation is not much different than that from a flat surface. A vertical mulched slot placed at the bottom of the slopes, as shown in figure 1B, causes deeper penetration of the water and a corresponding reduction in evaporation. The ridges formed by the microwatershed slopes were intersected every 15 m with a check dam to eliminate water flow in the vertical mulch slot along the rows.

MEASUREMENT OF CUMULATIVE EVAPORATION

The cululative evaporation for the season (June 12 to September 29, 1972) was determined by the initial and final water contents in the soil profile to a depth of 180 cm and the rainfall for the season. Soil water content in the profile was measured at the top, midway down the slope, and at the bottom of the runoff slope in each plot. The water loss by evaporation from the check plots could not be separated from runoff loss since the surface runoff was not measured. The assumption was made that the evaporation from the microwatershed plot without vertical mulch was approximately the same as that from the check plot with no surface runoff as suggested by Fairbourn and Gardner (1).

PREDICTION OF CUMULATIVE EVAPORATION

The cumulative evaporation from the treatment plots was predicted as well as measured. The predictions were carried out according to the procedure presented by Gardner (2, 3). The calculation was done in two parts. The evaporation for the slope area was based on the water that infiltrated into the slope after the runoff was subtracted. The evaporation calculation for the runon area was based on the rainfall plus the runoff water from the slope area. Thus, an estimate of the amount of water that ran off after each rain and the ratio of runoff to runon area was needed for the calculations.

The runoff water from each rain was estimated using a linear regression equation calculated from data supplied by Mickelson 2/. These data were runoff amounts for individual rains on similar runoff slopes on the same soil as that used in this experiment. The equation was:

$$y = 0.986x - 0.51$$

where:

y = runoff in centimeters of water

x = centimeters of rainfall applied

The correlation "r" value is 0.96. This equation indicates that for the slope involved in this experiment, after the surface storage and initial rapid infiltration of approximately 0.5 cm is satisfied, essentially all the water runs off.

The runoff to runon area was determined to be approximately 3:1 with a runoff slope length of 75 cm on each side of a 50-cm wide runon area, which contained the mulch slot. The vertical mulch material was assumed to have no direct effect on the evaporation calculation. An example of the determination of the reapportionment of the rainfall for the evaporation prediction is as follows: If 1 cm of rain fell and the runoff was calculated to be 0.6 cm, then the water that infiltrated into the slope was 0.4 cm, which would be used for calculating evaporation from the slope. The total water on the runon area would be 1 cm rain plus 3 x 0.6 cm or 2.8 cm. The evaporation averaged for the total area would be three times the evaporation from the runoff slope plus the evaporation from the runon area all divided by four. The cumulative evaporation was calculated for each area for the season, and then the average was calculated using the totals for the season.

RESULTS AND DISCUSSION

The cumulative evaporation amounts calculated from measured soil water content data for the microwatershed with and without vertical mulch for the 1972 growing season were 11.5 cm and 14.4 cm, respectively, showing a reduction in evaporative loss of 2.9 cm due to the mulch system. The corresponding predicted amounts were 11.0 and 13.5 cm for the corresponding treatments. The initial water in the soil on June 12 was neglected in the prediction since its effect was approximately the same on all treatments. This accounts for the difference between predicted and measured evaporation values. The calculated values were close enough to the measured values to make the analysis reasonable for other cases such as those discussed below.

The effect of the amount of seasonal rainfall on the cumulative evaporation was examined both for the check treatment and the microwater-

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2/ Rome Mickelson, private communication. Central Great Plains Field Station, Akron, Colo.

shed with vertical mulch treatments. Some or all of the individual rains must be changed in order to change the total seasonal rainfall, and the way that the individual rains are changed affects the seasonal cumulative evaporation. The approach taken here was to adjust each rainfall amount by the same percentage as the adjustment necessary for the total rain. The 1972 seasonal rainfall is presented in table 1. Figure 2 shows the relationship between the seasonal total rainfall and the predicted cumulative evaporation for the season. The figure shows that for the check treatment the cumulative evaporation equals the rainfall up to about 4 cm rain. Beyond this amount of rain, the cumulative evaporation is less than the rainfall, indicating a storage of water in the profile. Cumulative loss for the vertical mulch plot is even less than that for the check plot, indicating an even greater storage of water due to the microwatershed-vertical mulch system. At 25 cm seasonal rainfall, the runoff system would reduce the cumulative evaporation by 18 percent when compared with the check loss. The measured cumulative evaporation losses from the check and the microwatershed with the vertical mulch plots are also shown in figure 2.

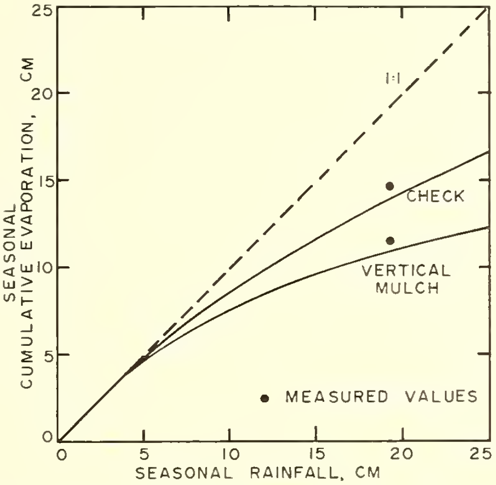

FIGURE 2.--Seasonal cumulative evaporation vs. total rainfall based on the rainfall distribution for the 1972 growing season for 3:1 runoff-runon ratio.

The ratio of runoff to runon area has a major effect on the amount of water available for plant growth. The ratio depends on the total seasonal rainfall and its distribution. The effect of the ratio on cumulative evaporation was examined by predicting the evaporation for runoff and runon areas for the various ratios and calculating the average loss for each ratio. As the runon area is increased in width with the runoff area width being held constant, the horizontal water infiltration into the runoff slope area will decrease in importance. Thus, a vertical mulch will decrease evaporation with increasing runon area width.

Figure 3 shows that the water loss by evaporation increases rapidly as the runon area increases in width (the ratio of runoff to runon area changes from 1:1 toward 1:2, etc.). Curve A shows the cumulative evaporation when the assumption is made that the water spreads evenly across the entire runon area. If, for example, the assumption were made that the water would spread only 0.75 m beyond the end of the runoff slope, then the average cumulative evaporation would be less than the

TABLE 1.--Rainfall at Akron, Colo., during the 1972 growing season

Date	Evaporation time after rain	Rainfall 1/	Date	Evaporation time after rain	Rainfall 1/
	Days	Cm		Days	Cm
June			Aug.		
10	6	0.28	1	1	1.37
16	2	.18	2	1	.05
18	4	.58	3	1	.23
22	2	.66	4	5	.15
24	3	.20	9	2	.13
27	6	.23	11	9	.38
July			20	2	.58
3	1	.43	22	2	.05
4	4	.15	24	1	3.18
8	3	.25	25	7	.31
11	1	4.70	Sept.		
12	10	1.85	1	1	.25
22	3	.13	2	6	1.45
25	2	.58	8	2	.13
27	5	.08	10	19	.03

1/ Total rainfall = 18.28 cm.

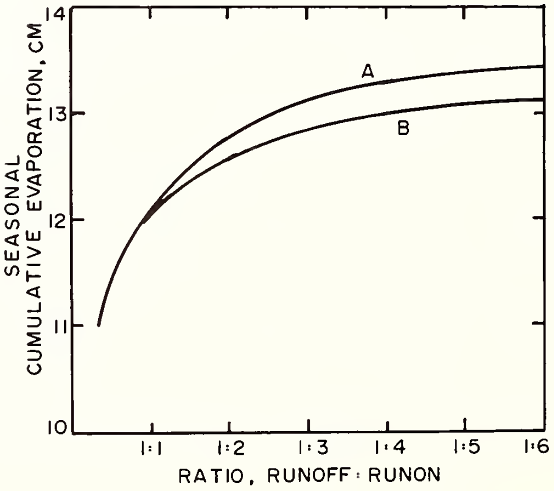

FIGURE 3.--Seasonal cumulative evaporation vs. the ratio of runoff area to runon area for the 1972 growing season rainfall.

case where the water spread evenly as shown by curve B in figure 3. The dry, flat area between the wetted runon areas would not be affected by the treatment but is included in the calculation of the average loss.

The farming system would determine the width of runon area. The runoff slope width would then be determined by the amount of runoff water needed when compared with expected rainfall and the necessity of getting the water to run to the center of the farmed area.

The percentage of rainfall that runs off during the season is another variable to be considered. The equation developed from Mickelson's data indicated that after the "surface storage" was satisfied, subsequent infiltration could be neglected. This would not be the case if the soil water had a higher infiltration rate due to soil properties or slope of the runoff area. To examine the effect of the percentage of runoff on cumulative evaporation, the runoff percentage was changed by changing the surface storage term in the equation, and then cumulative evaporation was calculated.

The percent reduction of evaporation (below that for zero runoff) that was caused by the change in the storage term is plotted against runoff in figure 4. This curve only applies for a 3:1 runoff-runon ratio and 18 cm seasonal rainfall. The curve shows that the maximum reduction in evaporation, due to concentrating the water, would be 50 percent. Further reduction for the field data corresponded to 55 percent runoff. Further reduction in evaporation, by spraying the runoff slopes with cementing or waterproofing agents, would have to be considered in terms of factors such as the cost of applying the material and the potential gain in water for plant use.

The data analysis shows that the potential for reducing evaporation is great enough with the microwatershed-vertical mulch system, even without special treatment of the runoff slopes, to merit serious consideration of this system as an alternative in low rainfall, nonirrigated areas. There appears to be a potential for decreasing evaporative loss of water by up to 50 percent.

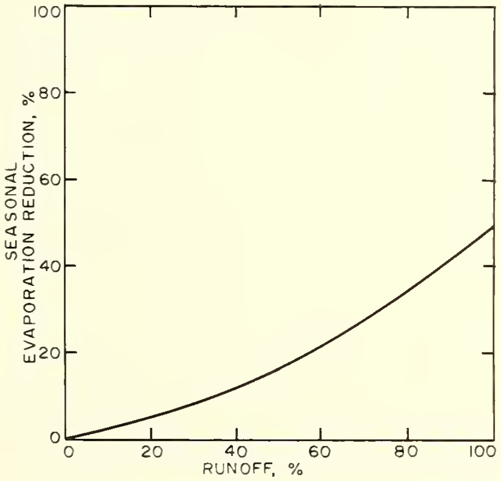

FIGURE 4.--Percent reduction in seasonal cumulative evaporation as affected by percent runoff for the 1972 growing season rainfall for 3:1 runoff-runon ratio.

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USING PARAFFIN AND POLYETHYLENE TO HARVEST WATER FOR GROWING SHRUBS

Earl F. Aldon and H. W. Springfield 1/

INTRODUCTION

In the water-scarce Southwest, a small additional increment of water may dramatically affect survival of newly planted vegetation. Harvesting water artifically offers possibilities for extablishing woody species on harsh sites where conventional methods of vegetation establishment may not be successful.

Of a number of techniques tried, the most effective appears to be to install a sheet of black polyethylene around the stem of the plant. In New Mexico, a 9-ft^2 sheet of black polyethylene functioned as a miniature "trick tank" that caught water and funneled it to the shrub planted in the center (8). Similar 9-ft^2 sheets of 4-mil black polyethylene dramatically improved survival and growth of pine seedlings in Nevada (2). The plastic made more water available to the seedling trees, and extended the availability of water later into the critical dry season. In Idaho, ponderosa pine seedlings surrounded by 4-mil black polyethylene survived and grew better than untreated plants (5). In Montana, plastic sheeting around shrubs has improved establishment on mine spoils (4).

Another approach is to waterproof the soil. Artificially created hydrophobic soil surfaces may improve the survival and growth of shrubs in arid zones. Much research has been done to develop materials and methods for waterproofing rainfall catchments. Asphaltic materials have been commonly used. The effectiveness of asphalt depends not only on the characteristics of the material itself, but also on the chemical composition, texture, structure, and moisture content of the soil (7). According to Myers and Frasier (6), hydrophobic materials work best on nonexpansive loamy sand and sandy loam soils.

A recent development is the use of paraffin wax, applied as granules or flakes on top of the soil. The wax melts and forms a water-repellent soil surface that sheds water. In central Arizona, wax-treated plots yielded 90 percent of the rainfall, while only 30 percent ran off untreated plots (3).

The objectives of the studies reported in this paper were to determine the yield of water and growth of shrubs in small plots treated with either paraffin or black polyethylene.

METHODS

This study was conducted during the summer of 1973 at Santa Fe, N. Mex., at an elevation of 6,950 feet and annual precipitation of 12.5 inches. Soil at the study site is a calcareous silt loam. In this study, 27 plots, each 9 ft^2, were shaped to provide shallow basins 3 inches deep (fig. 1). Two treatments and a control were randomly assigned:

1/ Principal hydrologist and range scientist, Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Albuquerque, N. Mex.

1. Black polyethylene, 4 mils thick, 9 ft^2, with the outer edges held in place by soil and the center portion by two or three small stones.

2. Paraffin, ground in a powder shredder, applied at a rate of 3/4 lb/ft^2 to a 4-ft^2 area in the middle of the plot. The paraffin had a melting point of 120° F.

3. No treatment.

The effective water-collecting area within each plot was 2 by 2 ft due to 6-inch borders of soil built up around each plot to prevent runoff water from escaping.

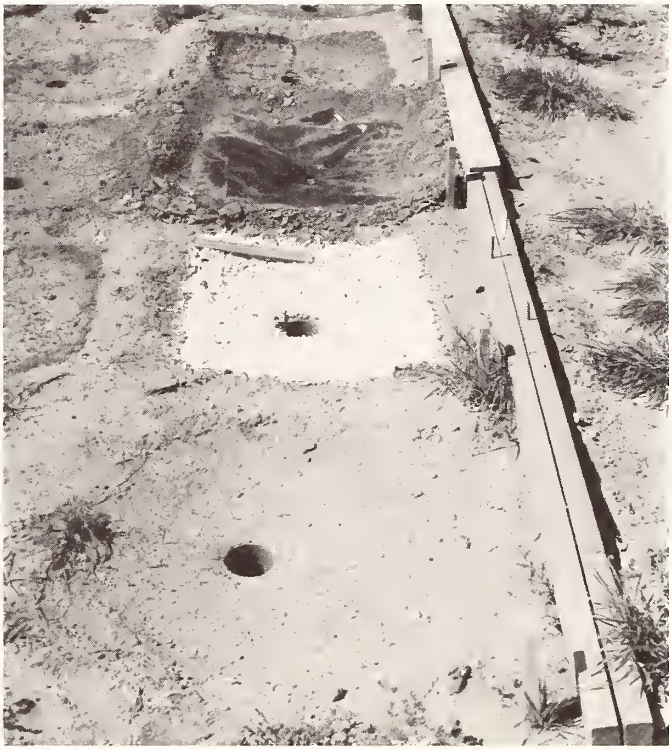

FIGURE 1.--Water-harvesting plots at Santa Fe, N. Mex., showing glass cylinder in center of each plot (front to back: check, unmelted paraffin with 1-foot ruler, polyethylene).

A 2-month-old transplant of fourwing saltbush (Atriplex canescens (Pursh.) Nutt.), grown by special techniques (1), was planted in each of the three treatments and replicated five times. Plants were 3 inches tall when planted.

Glass cylinders (sealed at the bottom), 16 inches tall and 3-5/8 inches inside diameter, were installed at random in three plots of each of the three treatments. The cylinders were buried in the soil in the center of the plots so that the top of the cylinder was flush with the bottom of the basin. A hole was cut in the polyethylene the same size as the cylinder. The ground paraffin was similarly placed so that, as it melted, it fused against the outer edge of the cylinder.

Temperature probes were also installed in three plots of each of the three treatments. The mercury-filled probes were installed 1 inch deep in the soil prior to application of the paraffin or polyethylene. All probes were connected to weekly recorders. Shaded soil (1 inch deep) and shaded air temperatures also were monitored. Calibrated gypsum soil moisture blocks were installed 3, 6, and 12 inches deep on two plots each of the three treatments. They were read weekly.

Thus, treatment and plot layout was as follows:

Treatment	Number of plots
Check with--	
No Treatment with transplants	3
Transplant and temperature probe	1
Transplant, temperature and moisture probes	1
Temperature and moisture probes	1
Glass cylinder for runoff collection	3
Polyethylene with--	
Transplants	3
Transplant and temperature probe	1
Transplant, temperature and moisture probes	1
Temperature and moisture probes	1
Glass cylinder for runoff collection	3
Paraffin with--	
Transplants	3
Transplant and temperature probe	1
Transplant, temperature and moisture probes	1
Temperature and moisture probes	1
Glass cylinder for runoff collection	3
Total plots	27

Precipitation was measured in a standard rain gage on the site after each storm during the period July 4 to October 1. Water collected in the cylinders was measured and removed after each storm. Depth of water was converted to area-inches.

Size of the shrub plants was determined by periodic measurement of height and crown diameter. Size index was computed by multiplying height times crown diameter (8).

Nine additional random plots were installed adjoining the first study in August 1973 to determine if the rate of application of ground paraffin would affect water yield. Paraffin at rates 1/2, 3/4, and 1 lb/ft^2 was put on the new plots, and each rate was replicated three times. Plot size and shape, installation of glass cylinders, and methods of measurement were the same as for the other experiment. No temperature or moisture probes were installed on these plots.

RESULTS

Runoff

Ten storms, ranging in size from 0.04 to 0.41 inch, were used to analyze increased runoff due to the treatments (table 1). Runoff from three larger storms (over 0.45 inch) could not be measured due to the limitations of the catchments. Both treatments added an average of 0.75 inch more moisture to the growing shrubs than what might be expected from shaping plots but did not add a wax or polyethylene covering. This difference was statistically significant (table 1).

TABLE 1.--Runoff on 4-ft^2 plots from 2.04 inches of precipitation (10 storms of less than 0.45 inch) at Santa Fe, N. Mex.

	Runoff		
Treatment	Amount	Precipitation	Increase
	Area-inches	Percent	Percent
Control	0.57	28	--
Paraffin	1.39*	68*	40
Polyethylene	1.26*	62*	34

*Significantly different from control at 0.05 level.

Size of fourwing saltbush plants reflected this difference in water yield. Seventy-five days after planting, shrubs grown in plots treated with polyethylene were largest, while those in untreated plots were smallest (fig. 2):

	Height (inches)	Size index (height x crown diameter)
Check	6.3	44.7
Paraffin	8.4	87.0
Polyethylene	14.6	184.1

Water yield from 0.67 inch of precipitation was not improved by higher rates of paraffin application:

Paraffin (pounds)	Runoff (area-inches)
0	0.07
1/2	.48
3/4	.45
1	.48

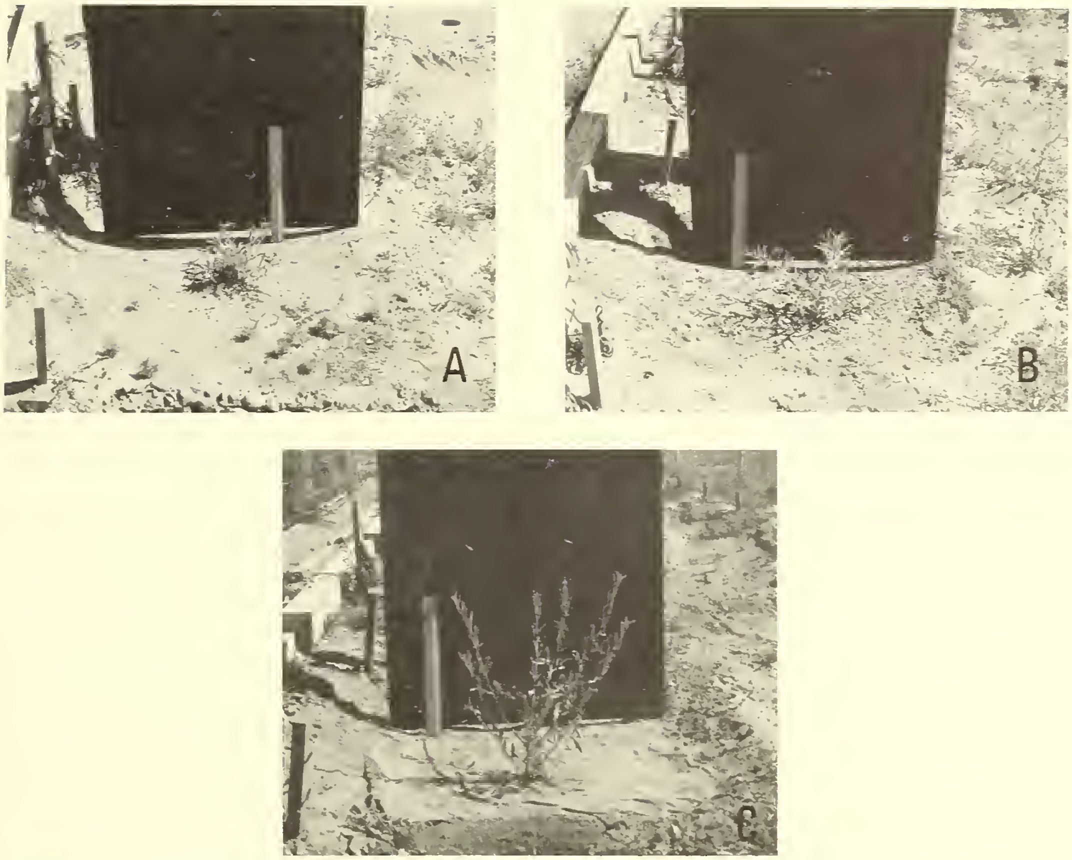

FIGURE 2.--Fourwing saltbush plants grew largest under polyethylene: A, check; B, paraffin; C, polyethylene.

Temperature

Temperatures 1 inch deep in the soil were higher under paraffin than under black polyethylene during the middle of the day throughout the duration of the study. For example, in the first 2 weeks, temperatures at noon averaged 97° F under paraffin compared with 86° under polyethylene. Soil temperature generally was highest about 3 pm, when the air temperature in the shade averaged only 81°, but the soil under paraffin measured 130° and under polyethylene, 99° (fig. 3).

Soil Moisture

Soil moisture was adequate for shrub growth throughout most of the summer, regardless of treatment. However, more moisture was available in plots treated with either paraffin or polyethylene than in untreated plots, particularly in late August and early September. Moisture tension at the 6-inch depth remained at 15 bars for at least a week in the check plots. Toward the end of the summer, from September 20 to October 20, more moisture was measured in paraffin-treated plots than in the others.

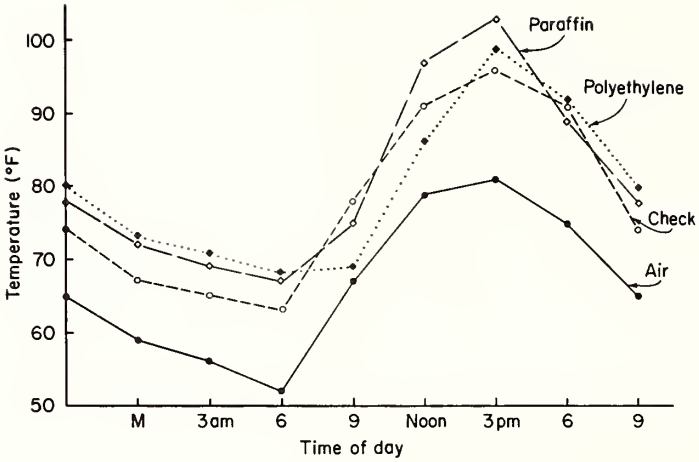

FIGURE 3.--Temperatures 1 inch deep in the soil beneath paraffin and black polyethylene, compared with untreated check and shaded air temperatures (averages of 3 plots for each treatment during the first 2 weeks).

Field Verification

In addition to the above studies, 50 transplants of Siberian peashrub (Caragana arborescens Lam.) were planted in surface coal mine spoils near Gallup, N. Mex., early in August 1973. Shrubs were planted in shallow basins much like those reported in the above studies. Paraffin was applied on the sides of 10 basins at rates of 1/2, 3/4, or 1 lb/ft^2, at random. Black polyethylene sheets also were installed around 10 of the plants, while the remaining 10 were left untreated.

Rainfall for the first 2 weeks after planting was nil. For the remainder of the study (2 months), rainfall amounted to 1.53 inches in 10 small storms (less than 0.45 inch). One additional storm amounted to 0.59 inch.

All plants survived this first growing season. Plant height alone showed no differences amoung treatments, but plant vigor differences (on a scale of 1 for poor vigor to 3 for good vigor) were apparent:

Treatment	Vigor rating
Check	1.4
Polyethylene	2.3
1/2 paraffin	1.7
3/4 paraffin	1.8
1 paraffin	1.8

Soil moisture readings partially explain these plant vigor differences. For example, soil moisture under paraffin treatments averaged 20 percent higher than under no treatment midway in the study. By the end of the growing season, soil moisture was depleted, but there was slightly more moisture under the paraffin.

SUMMARY

Paraffin and polyethylene catchments were equally effective in harvesting runoff water from small storms (less than 0.45 inch). They caught an extra three-quarters of an inch of water compared with untreated basins during the summer rainy season at a typical semiarid site in the Southwest. A half-pound of ground paraffin per square foot harvested as much water as higher rates of paraffin. Two-month-old fourwing saltbush transplants grew more during their first growing season with this increased moisture from treated plots. Soil moisture remained available to the plants throughout the study, and was higher under treatments.

These methods of water harvesting were tested further on surface coal mine spoils in western New Mexico. Siberian peashrub transplants showed better vigor, and soil moisture measurements were about 20 percent greater under the treated plots.

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DISCUSSION

SESSION IV, Part 1--Richard Frevert, Chairman

D. FINK: What was the soil preparation between crops? Also, do you forsee only having to cultivate the runon area with yearly compaction only of the runoff area?

M. FAIRBOURN: We ran over our microwatersheds with the hourglass roller as described in the presentation. The operation was primarily to remove old stubble and to compact the slopes. It was necessary to replace the vertical mulch. We fertilized the row areas and worked in the fertilizer with a small rototiller. We expect tilling of the runon area to be adequate.

H. BOUWER: What was the technique for predicting evaporation from the soil?

H. GARDNER: The technique for predicting evaporation is rather involved so I have not explained specifically how it was done but rather have referred to another paper, which explains it rather thoroughly.

D. WOOLHISER: In your analysis of microwatershed efficiency, when you reduced rainfall amounts per storm by a fixed percentage, was this an attempt to simulate a drier year at the same location or to simulate the rainfall for a different location?

H. GARDNER: The reduction of rainfall by a percentage was purely arbitrary. The evaporation prediction could have been done for any rainfall distribution that could have represented rainfall from any location in the semihumid areas.

D. FINK: Why did polyethylene do better than wax in establishing four-ring saltbush, and which of the two treatments did you prefer?

E. ALDON: Paraffin is an easily applied and low-cost field method to harvest water. This is why we tested it. It proved equal to polyethylene in harvesting water, but shrubs do grow more under polyethylene.

G. FRASIER: Would you comment on the rate of wax which you would apply based on your previous studies?

E. ALDON: We would now try much lower rates of wax.

SESSION IV, Part 2--Richard Frevert, Chairman

PRECIPITATION ENTRAPMENT FOR EVAPORATION SUPPRESSION [1]

James R. Hoover [2]

INTRODUCTION

Throughout many of the Great Plains States, moisture conservation is important for good crop yields. The problem of moisture stress in crop growth in this region is the result of the relatively low amount and erratic distribution of percipitation as shown in figure 1, the amount of evaporation loss from the soil, and the related soil moisture storage deficiency.

The severity of the moisture problem can be determined for a given location by substituting climatic data for the location into relationships that have been reported in the literature. For example, at Madison, S. Dak., which is in the western fringe of the subhumid corn belt region,

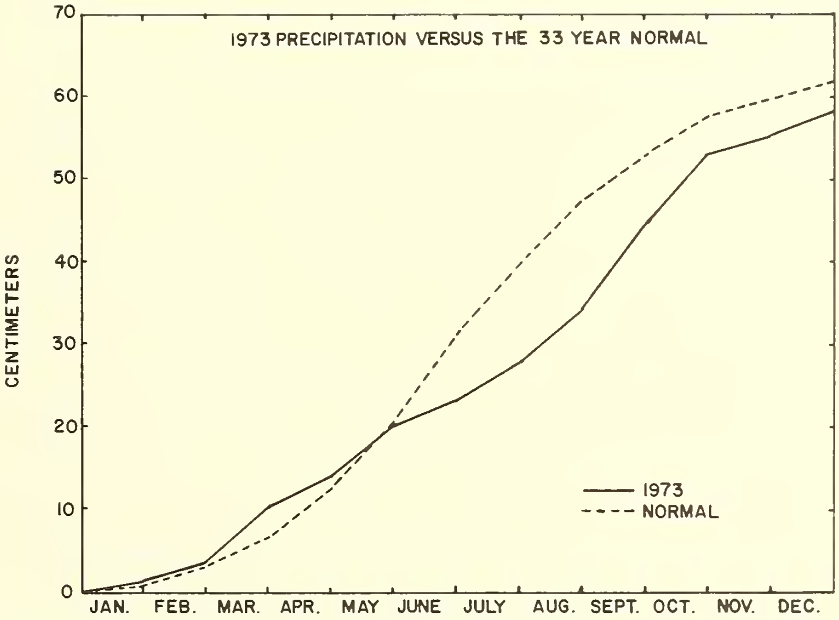

FIGURE 1.--Precipitation distribution at Madison, S. Dak.

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[1] Contribution from the Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the South Dakota State University and the South Dakota Agricultural Experiment Station (SDAES), Brookings, S. Dak.

[2] Agricultural engineer, Soil, Water and Air Sciences, ARS, USDA, at Orono, Maine (formerly at Brookings, S. Dak.).

the normal average annual precipitation is 62.1 cm, with 29.0 cm occurring during the 136-day average frost-free growing season (15). Thus, only 47 percent of the precipitation occurs during the growing season. Precipitation has varied from 41.8 to 86.5 cm per year during the 33-year period of record. Assuming that 47 percent of the rainfall during these years came during the growing season, 19.7 to 40.7 cm of precipitation occurred during this period. These erratic variations from the long-term mean result in moisture being the critical factor in corn growth. Spring recharge is inversely proportional to the total soil moisture at spring thaw (16), thereby removing some of the variation in yearly spring soil water storage. About 146 percent (2) of the normal precipitation during the growing season is required for evapotranspiration (ET), therefore, 42.3 cm of moisture is needed for ET. About 21.6 cm is utilized, for 8,400 kg/ha corn yield (8), as transpiration (T), which leaves about 20.7 cm for evaporation (E). This means that E is about 49 percent and T is 51 percent of the total moisture used during the corn growth, which is within the range, $50 \leq E \leq 70$ percent found by Peters and Russell (13) and near the 56 percent given by Harrold et al. (8).

From the preceding data, the importance of soil moisture storage at planting time becomes apparent. For example, during a normal year, soil moisture storage should be about 13.3 cm, which is approximately the 14 cm that Holt et al. (9) have indicated will be available only 67 percent of the time. They also indicated that during a dry year each additional centimeter of moisture stored in the soil at planting time may produce an additional 265 kg/ha.

The citations listed above may be summarized as: (1) Corn uses water at a rate exceeding the rainfall; (2) corn can extract soil moisture to a depth of 152 cm, but summer rainfall and irrigation do not penetrate deeper than 61 cm; and (3) evaporation accounts for a large amount of water loss from a cornfield in this region. These factors emphasize the importance of soil moisture storage and evaporation reduction.

Proposed solutions to the problem of moisture stress involve the concepts of transporting, collecting, and deep placement of precipitation into the soil profile and evaporation suppression to keep the additional moisture stored for plant use. Soil moisture storage can be increased by precipitation runoff inducement (transporting) to a concentrating point (collecting) where the rainfall is conducted to a point deep within the profile (deep placement) and infiltration can occur. Soil moisture stored at depths greater than 61 cm is not considered subject to loss by evaporation. Previous research with deep placement of precipitation consisted of a vertical mulch (1, 3, 4, 5, 6), which resulted in limited success, probably due to the wick effect of the mulch. The deep placement of precipitation permits the trapping of large storms due to the greater portion of the soil profile being accessible to rainfall infiltration, which results in less runoff. In addition, small storms penetrate deeper when the rainfall is less subject to evaporation (7, 14, 18). Soil sealants used to induce runoff to the concentrating point, also reduce the evaporation. Sealants that cover 90 percent or more of the soil surface can reduce evaporation by 75 percent (17). Thus, the precipitation saved is available for plant growth.

PROCEDURE

Experiments were developed to evaluate the soil moisture management concepts of precipitation capture and storage in the soil profile for plant growth by deep placement and evaporation suppression. The research was conducted during a 5-year period (1969-73) on an Egan silty clay loam, for which the soil characteristics are given in table 1 (12). Data collected included: precipitation, soil and air temperature, soil moisture, and crop yields.

TABLE 1.--Water release data for Egan silty clay loam

Horizon	Depth	Bulk density	Particle size			Available water 1/10 to 15 bars
			Sand	Silt	Clay	
	Cm	G/cm^3	------Percent------			Cm
Ap	0-18	1.08	19.8	51.2	29.0	4.2
B_{21}	18-41	1.17	19.8	49.2	31.0	4.6
B_{22}	41-58	1.23	18.8	51.2	30.0	3.7
B_{3ca}	58-76	1.24	20.6	49.4	30.0	3.5
C_{1ca}	76-97	1.28	22.6	45.4	32.0	4.1
IIC_{2ca}	97-152	1.28	40.4	23.6	36.0	9.3
Total						29.4

Deep Placement

To evaluate the effect of deep placement of precipitation, an experiment (diked to prevent runoff) was conducted involving (1) a check, (2) a 7.6-cm-diameter core hole 61 cm deep located on a 102-cm grid, and (3) a core hole plus surface sealant treatments. The objective of this experiment was to determine the amount of moisture from both small and large storms that could be saved by entrapment in the soil profile and used for plant production.

An experiment was run to evaluate the concept of precipitation runoff inducement to a concentrating point where infiltration was the mechanism for deep placement. Runoff inducement was by use of a surface sealant consisting of 4-mil clear plastic or DCA-70, a chemical produced by Union Carbide as a soil stabilizer, placed on the area between the rows, which was ridged to promote runoff to the rows. The treatments were plastic placed in strips, DCA-70 latex applied in strips, and a check. The plastic strip treatment covered 90 percent or more of the soil surface, which should reduce evaporation during the growing season to about one-fourth the evaporation from the check treatment (17).

Evaporation Suppression

Another experiment was set up to evaluate concentrations and rates of application of soil surface sealants applied to suppress evaporation. The chemical DCA-70 was recommended by Myers (10, 11, 14) as probably the best treatment available to use for evaporation suppression. In addition to trying various concentrations and application rates, the treatments included a check and various clear plastic cover techniques, such as (A) a solid cover with and without precipitation added (8), and (B) plastic strips between the rows (18).

Therefore, our procedure was to evaluate the soil moisture management concepts listed previously and to compare these results with those obtained on plots at the same location and treated in the same manner as the best soil moisture management practices reported in the literature (8, 13, 17, 18). This systematic method of comparing soil moisture, water use efficiency, soil temperature, and corn yields eliminates the errors associated with the extrapolation of field data from other locations collected during different years under completely different climatic and soil conditions. The climate at these other locations is quite different from that found at Madison.

RESULTS

The effectiveness of the given treatments will be evaluated by analyzing the grain yields, water use during the growing season, and water use efficiency. The results are presented in metric units which are equivalent to the following English Units: 1 cm = 0.39 inch, 1 ha = 2.47 acres, 1 t (metric ton) = 1,000 kg, 1 t/ha-cm = 37.77 bu/acre-inch.

Deep Placement

During the first 3 years, DCA-70 soil stablizer and dust control agent was used on the core-hole-plus-sealant treatment of the deep placement experiment. The DCA-70 was diluted with water at a 1:2 concentration and applied at the rate of 2.26 liters per square meter (one-half gallon per square yard). This application rate was chosen because it completely infiltrated to a depth of 0.6 cm within 15 minutes. The core holes were covered during the sprinkling application of the DCA-70 to prevent the latex from sealing the wall and bottom of the core holes.

Soil moisture storage data in figure 2 shows very little difference

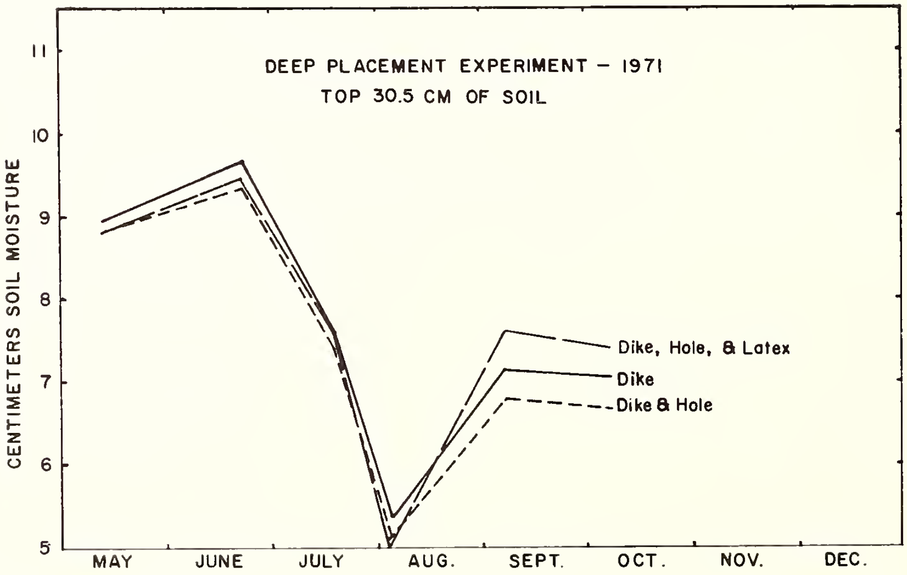

FIGURE 2.--Soil moisture in the top 30.5 cm of soil for the deep placement experiment.

from treatments within the top 30.5 cm of the soil profile, thus indicating that the sealant did not change the amount of soil moisture in this area of the profile. Hence, inducing the runoff of small storms into the core hole, where it would infiltrate at the 61-cm depth and where it would not be subject to evaporation, did not affect the soil moisture storage of the top 30.5 cm. The core-hole-without-sealant-treatment retained less soil moisture stored in the 152 cm profile than the other treatments as shown in figure 3. This implies that the core hole area, when no surface sealant was used, evaporated more water than

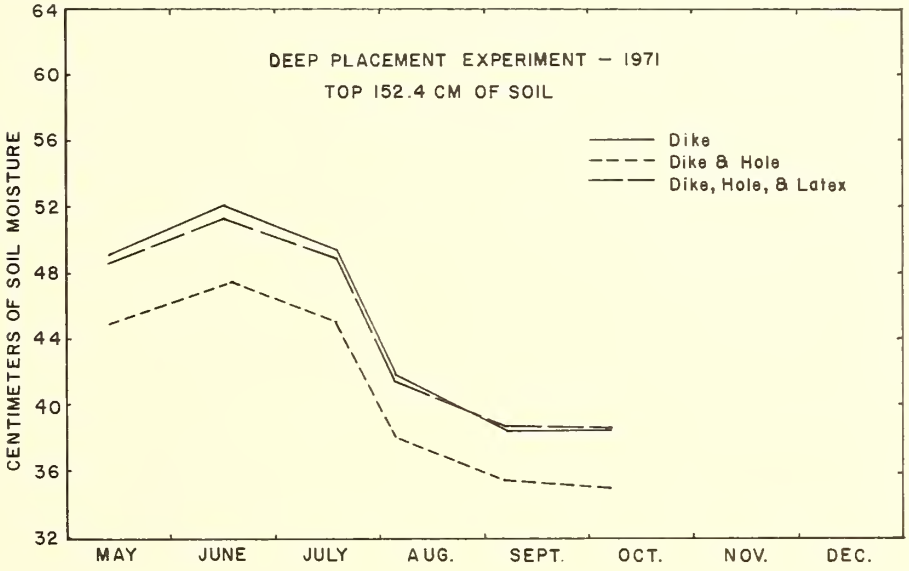

FIGURE 3.--Soil moisture in the top 152.4 cm of soil for the deep placement experiment.

was harvested by this treatment. Also, the sealant treatment saved or harvested more moisture than the check or core-hole-only treatments and trapped it within the profile in the fall until seedbed preparation.

During seedbed preparation, the seal was destroyed, at which time large amounts of evaporation or percolation may have occurred before the surface seal was replaced. After the sealant was replaced, the rate of water loss during the growing season was about the same for all treatments in the top 152 cm of soil. Therefore, the seal material was replaced with 4-mil clear plastic after 1971.

The grain yields are shown in table 2. No treatment yields were significantly different until the latex was replaced by the clear plastic covering. The yields for the core-hole-plus-plastic-cover treatment were significantly higher than for the check or the core-hole-only treatments.

The seasonal rainfall and water use are given in table 3. The water use efficiency is given in table 4, which shows that the core-hole-plus-sealant treatment always utilized the available water more efficiently. The yield data plotted against water use efficiency in figure 4 is approximately a linear relation, indicating that water use is directly proportional to the yields obtained in this experiment. Since none of the plotted points fell far above the straight line, the yield potential had not been reached.

TABLE 2.--Grain yields from the deep placement experiment

Year	Check	Core hole	Hole and sealant
	T/ha	T/ha	T/ha 1/
1969	5.41a	5.18a	5.33a 2/3/
1970	4.83b	4.14b	4.74b 2/
1971	3.72c	3.13c	4.41c 2/
1972	4.24d	4.29d	5.36e 4/
1973	6.84f	6.95f	7.84g 4/

1/ Metric tons (T).

2/ Sealant was DCA-70; concentration, 1:2; rate, 2.26 l/m^2.

3/ Letters following yields refer to significant difference comparisons within a given year at the .01 level with Duncan's New Multiple Range Test.

4/ Sealant was clear, 4-mil plastic, wired to the ground, perforated at core hole location.

TABLE 3.--Water use during the growing season on the deep placement experiment

Year	Seasonal rainfall	Average initial soil moisture	Water use		
			Check	Hole	Hole and sealant
	Cm	Cm	Cm	Cm	Cm
1969	22.1	28.7	20.1	20.1	19.7
1970	26.2	55.3	43.3	43.3	44.8
1971	23.3	50.1	37.0	35.6	36.1
1972	30.6	62.5	31.3	32.1	34.2
1973	17.0	60.9	33.5	33.9	37.0

TABLE 4.--Water use efficiency on the deep placement experiment

Year	Grain yields		
	Check	Core hole	Hole and sealant
	Kg/ha-cm	Kg/ha-cm	Kg/ha-cm
1969	269.1	257.4	270.4 1/
1970	100.0	95.5	105.8 1/
1971	100.3	88.1	122.0 1/
1972	135.5	133.6	156.6 2/
1973	204.3	204.8	212.0 2/

1/ Sealant was DCA-70; concentration, 1:2; rate, 2.26 l/m^2.

2/ Sealant was clear, 4-mil plastic, wired to the ground, perforated at the core hole location.

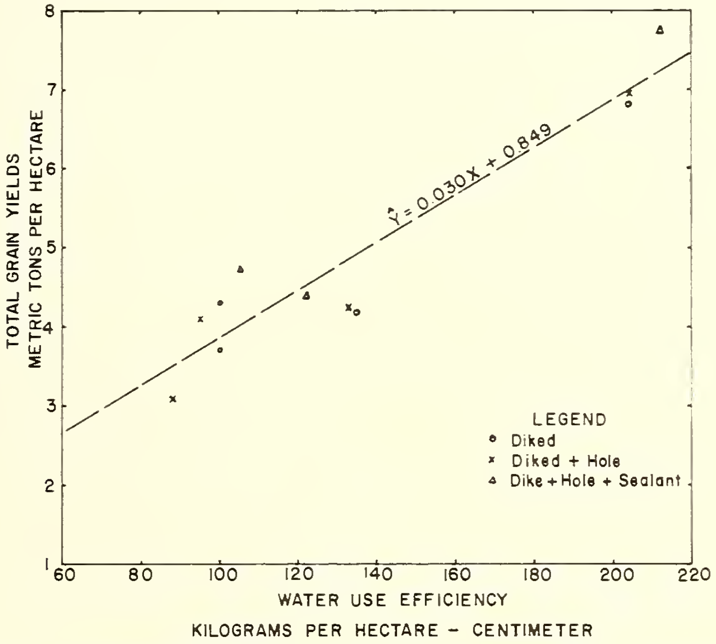

FIGURE 4.--Grain yields versus water use efficiency for the deep placement experiment.

Deep placement by runoff inducement to a concentrating point, where the infiltration resulted in soil moisture stored for plant use, was evaluated by strip application of latex or plastic on the ridge between the corn rows where 90 percent of the soil was covered. The yields are shown in table 5 and the water use efficiencies are given in table 6. The plastic-strip treatment stored the most water and produced the highest yields. The results from this plastic-strip treatment indicated that the latex treatment on the deep placement experiment should be replaced by plastic strips between the rows with an X cut above each core hole.

This modification was superior to the latex seal as indicated by the yield for this treatment.

Evaporation Suppression

Latex Seal

During 1969-71, the latex sealant (DCA-70) was evaluated at different concentrations applied as a solid sheet and as strips between the corn rows. Corn yields for the different latex treatments are given in table 5. Although yields sometimes compared well with those for the plastic-covered plots during certain years, the results were not consistent. The latex cracked severely during very dry periods, did not penetrate more than 0.1 cm, and lost its effectiveness. Since this latex did not perform consistently well, as can be seen from the water use efficiencies given in table 6, it was replaced by the superior performing clear plastic.

TABLE 5.--Grain yields, in metric tons per hectare, from the sealant experiment

	Grain yields									
	DCA-70 concentrations							Plastic 1/		
Year	0:0	1:20	1:10	1:5	1:1	1:2	2:1	CS	CSW	PS
1969	4.88	4.97	3.84	3.68	4.35	5.06	5.27	3.63	----	5.88
1970	2/2.56a	3.86ab	----	----	3.96ab	3.90ab	----	2.70a	4.87b	5.14b
1971	3.87c	----	----	----	----	3.89c	----	----	----	4.69d

1/ Plastic treatments of complete seal (CS), complete seal with water (CSW), and plastic strips between the rows (PS).

2/ Letters following yields refer to significant difference comparisons within a year at the .05 level with Duncan's New Multiple Range Test.

TABLE 6.--Water use efficiency on the sealant experiment

	Grain Yields			
Year	Check	CS 1/	LS 1/	PS 1/
	Kg/ha-cm	Kg/ha-cm	Kg/ha-cm	Kg/ha-cm
1969	317.2	204.3	386.0	350.3
1970	78.3	215.62	114.8	134.1
1971	108.7	-------	109.0	146.6

1/ Plastic treatments of complete seal (CS), latex strips between the rows (LS), and plastic strips between the rows (PS).

Plastic Cover

The clear plastic cover was used on the deep placement and the sealant experiments. The plastic-covered treatments used in the sealant study consisted of completely sealed plots without precipitation, completely sealed plots with water added under the cover, and plots covered with plastic strips between the corn rows. The results of these treatments are given in tables 5 and 6. An additional advantage of using the clear plastic seal was the increase in soil temperature. The soil temperature at the 10-cm depth for the plastic treatment was 1.8° C higher than the check and 1.6° higher than the latex treatment, which would result in earlier and faster corn growth, and, hence, higher yields from the plastic-covered treatments.

CONCLUSIONS

Deep placement of precipitation within the soil profile was effective when coupled with the plastic surface sealant. Plastic strips placed on a ridge between the corn rows, where less than 10 percent of soil surface was exposed, gave superior corn yields and produced these yields at a higher water use efficiency. The clear plastic treatments resulted in higher yields because they decreased evaporation while increasing deep infiltration and soil temperature.

The chemical DCA-70 soil stabilizer and dust control agent was not consistently effective for inducing runoff or for evaporation suppression. The chemical was subject to cracking but did remain attached to the soil and stabilized the soil around the deep-placement core holes. The ideal surface treatment would consist of the durable, stretchable properties of the plastic and the soil bonding and stabilizing properties of the DCA-70 latex.

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CROP PRODUCTION BY WATER HARVESTING 1/

D. D. Fangmeier 2/

INTRODUCTION

Crop production in semiarid to arid areas of the world by water harvesting offers a method for utilizing limited quantities of rainfall. Water for plant growth is obtained by diverting the rainfall runoff from a contributing area to an adjacent cropped area. Two factors are important in determining the feasibility of this crop production scheme. First, does rainfall occur during a period favorable for plant growth, and, second, can sufficient runoff be obtained to maintain plant growth? The second factor is affected by the frequency and amount of rainfall and the portion of rainfall that can be collected from a contributing area.

The purpose of this study was to determine the feasibility of using runoff for crop production in southeastern Arizona without having water storage facilities. The data collected are also useful for verifying simulation models of this scheme. The study was conducted for four summers starting in 1970.

The University of Arizona Campbell Avenue Experiment Farm was the site selected. The area has an average summer rainfall of about 6 inches (2). A similar amount occurs during the winter months, but temperatures are too low for good crop production.

The topsoil at the site is a sandy loam to about 3 feet. Below the topsoil is a gravelly sand zone.

Since the study did not include contributing area treatment, most runoff was simulated using pumped water. A recording rain gage was installed near the center of the plots. The plots or basins consisted of a level area surrounded by a soil levee that could contain about 6 inches of ponded water.

A short-season grain sorghum was selected as the first test crop because its water use appeared to have a close correlation with the summer rainfall distribution. Grain sorghum requires about 24 inches of water under irrigated conditions (1). Thus, about four times the average rainfall is needed for maximum production.

During the third and fourth years of the study, cantaloupe, cucumber, squash, and watermelon or sweet corn were tested. These crops were selected because of their higher value and easy preparation for human consumption.

1970 RESULTS

Four cropped areas were established in 1970. The two main plots, 1 and 2, were approximately 100 by 45 feet, and water simulating runoff

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1/ Contribution from Arizona Agricultural Experiment Station, Soils, Water and Engineering Department, in cooperation with the U.S. Water Conservation Laboratory, Phoenix, Ariz. Journal Paper No. 2249 of the Arizona Agricultural Experiment Station.

2/ Agricultural engineer, Soils, Water and Engineering Department, University of Arizona, Tucson, Ariz.

from a contributing area was delivered through aluminum pipe. Plot 1 had a simulated contributing area three times the plot size, whereas plot 2 had one five times the plot size. It was assumed all rainfall would run off so the plots would receive four and six times the rainfall.

Both plots were planted to grain sorghum in 36-inch rows on June 29 and 30. Plot 1 was planted on the flat, whereas plot 2 was planted on small beds about 2 inches high.

Table 1 gives the dates and amounts of rainfall measured in the rain gage at the site. The first rain was received on June 28; however, this was not multiplied because the sorghum was not planted. The next rain was 0.57 inches on July 7. This was sufficient for germination and early growth until the rain of July 19.

Soil moisture samples were taken to a depth of 3 feet five times during the growing season. The soil moisture content varied between 10 and 19 percent (dry weight basis). Plot 2, which received more water, always showed higher soil moisture percentages than plot 1. No signs of plant stress were observed in either plot during the season. In fact, the rains of September 6 and 15 were not multiplied because adequate moisture was available to complete the season.

TABLE 1.--Data and amount of 1970 rainfall measured at the test site

Date	Rainfall
	Inches
June 28	1/ 0.92
July 7	.57
19	1.24
20	.92
Aug. 2	.14
3	.05
7	.31
10	.56
11	.10
14	.23
18	.28
23	.49
Sept. 2	.12
3-5	1.50
6	1/1.10
15	1/ .08
Total	8.61

1/ Rainfall not multiplied; 6.51 inches were multiplied.

Table 2 shows the yield and water data for 1970. Plot 1 has a slightly higher yield than plot 2, although plot 2 received more water. This could possibly be the difference between planting on the flat and planting on a bed. Both yields compare favorably with the 4,000 lbs/acre average yield for short-season irrigated grain sorghum under usual cultural practices. Some bird damage occurred in both plots. In addition to the grain, about 1 lb/foot of row (7.2 tons/acre) of forage was obtained. Data for all test plots were converted to an acre basis for easy comparison.

TABLE 2.--Yield and water data for grain sorghum in 1970

Plot	Yield 1/	Water received per plot
	Lbs/acre	Inches
1	3,440	27.2
2	3,200	36.9

1/ Average yield of four harvests converted to an acre basis.

Two plots having contributing areas sealed with polyethylene sheets were also established in 1970. Plot 3 was a single row or sorghum with a contributing area along one side. This was not satisfactory as too much levee had to be maintained relative to the cropped area. Plot 4 had four rows of sorghum planted in the bottom of 6-inch furrows. The contributing area consisted of sealed furrows. This also was not satisfactory as the plants were nearly killed by ponded water after a large rain. Both of these plots had lower yields than plots 1 and 2.

1971 RESULTS

In 1971, eight basins, about 12 by 50 feet in size, were established. Four 36-inch rows of sorghum were planted lengthwise in each basin on June 29. The first rain did not occur until July 16 (table 3). This did not reduce the germination, but emergence was about 2 weeks later than in 1970.

Four water treatments were used. They provided each basin with three, four, five, or six times the measured rainfall. The rainfall of 1.92 inches on August 16 could only be contained by the levees in basins receiving three times the rainfall.

The yield and water data for 1971 are given in table 4. Unfortunately, birds damaged most of the sorghum so the yields shown are lower than actual values. However, the yields would probably not be as high in 1970 because of the later germination. Germination 2 weeks later caused about a 4-week delay in harvest.

Eight soil moisture samples were taken to 3 feet in each basin during the season. The soil moisture percentages (dry-weight basis) varied from 3 percent on July 15 to 23 percent on August 16. Both percentages occurred in the top foot of soil. In late September, the soil moisture percentage dropped to about 6 percent in the upper 2 feet of soil. However, the plants showed no stress for lack of water and tensiometers indicated adequate moisture at 4 feet.

One basin, which inadvertantly received too much water after the July 16 rain, matured about 2 weeks earlier than all other basins. This

TABLE 3.--Date and amount of 1971 rainfall measured at the test site

Date	Rainfall
	Inches
July 16	0.23
19	.10
30	.77
Aug. 3	.63
7	.10
8	.05
9	.15
10	1.92
12	.45
14	.87
17	.62
19	.67
21	.50
Sept. 1	.55
30	.40
Oct. 16	1.05
Total	9.06

TABLE 4.--Yield and water data for grain sorghum in 1971

Basin	Yield 1/	Water received per basin 2/
	Lbs/acre	Inches
1	None	41
2	890	27
3	2,000	33
4	1,380	47
5	None	47
6	1,590	33
7	None	40
8	None	27

1/ All plots had some reduction in yield caused by birds. Those plots having no yield were completely harvested by birds.

2/ Basins would hold only three times rainfall after August 10 rain.

indicated the importance of having adequate moisture for germination and growth early in the summer.

1972 RESULTS

In 1972 several changes were made in the design of the experiment. Basin size changed to 12 by 43 feet and 15 by 43 feet, alternating in order. The crops planted were cantaloupe, squash, watermelon, and cucumber. The cucumber and cantaloupe were planted one row of each lengthwise in the small basins. One row each of watermelon and squash was planted in the larger basins. The row of squash was equally divided between zucchini and Mexican squash.

Three typical rainfall-runoff equations for treated watersheds were used to simulate the runoff from the contributing areas. 3/ The equations were:

$$V_1 = \frac{0.85}{12}(\text{inches rainfall} - 0.06)(3.5 \times \text{basin area})$$

$$V_2 = \frac{0.30}{12}(\text{inches rainfall} - 0.10)(10 \times \text{basin area})$$

$$V_3 = \frac{(\text{inches rainfall})\ (3 \times \text{basin area})}{12}$$

where V_1, V_2, V_3 represent the volumes of runoff from three treatments. These equations provided the basins with water about equivalent to four times rainfall. They were selected to determine the effect of contributing area treatment and if runoff from small rains is important.

Planting was completed July 7, and the first rainfall occurred on July 15 (table 5). The soil surface dried and crusted after the July 15 and 17 rains. This, plus planting too deep, delayed and reduced germination. The Mexican squash and cucumber emerged first, the watermelon and zucchini squash next, and cantaloupe last. The seeds were planted 1 to 1-1/2 inches deep to avoid high soil surface temperatures. Normally, they are not planted more than three-quarters of an inch deep.

The yield and water data for 1972 are given in table 6. The yields for cantaloupe, cucumber, and watermelon are good for the area. Many fruit were left on the vines because they did not ripen during the cool fall temperatures. The zucchini squash were killed by the squash vine borer. The Mexican squash were also affected. No Mexican squash yields are reported as they were harvested for seed. The vines of many plants spread beyond the levees around the basins, which compensates for missing plants. It also means yield may be influenced by basin size and shape. Unfortunately, possible effects of the three rainfall-runoff equations were masked by the high rainfall.

1973 RESULTS

In 1973, eight basins, 12 by 40 feet, were constructed. One-half row each of cataloupe, cucumber, Mexican squash, and sweetcorn were planted on June 26 in two rows lengthwise in each basin. The location was random except sweetcorn was on the north side to prevent shading of an adjacent row. The 1972 rainfall-runoff equations were modified by changing the constant multiplied by the basin area to give approximately two and a half, three, three and a half, and four times rainfall.

3/ Frasier, G. Personal communication. U.S. Water Conservation Laboratory, Phoenix, Ariz. June 1972.

TABLE 5.--Date and amount of 1972 rainfall measured at the test site

Date		Rainfall
		Inches
July	15	0.50
	17	.20
	24	1.00
	27	.18
Aug.	5	1.30
	7	.55
	12	.65
	31	.35
Sept.	1	.60
	7	.50
	9	.25
	18	1/.30
Oct.	3	.50
	4	1.65
	5	.45
	18	.75
	19	2.00
Total		11.93

1/ Last rainfall multiplied.

The dates and amounts of rainfall are shown in table 7. A total rainfall of 1.67 inches was received. The rain on July 5 of 0.25 inches was only sufficient to germinate a few plants that were in low areas in the basins. After mid-August, the growing season remaining was too short and the experiment was discontinued. Water added to two basins in late August resulted in germination of very few plants.

DISCUSSIONS AND CONCLUSIONS

The average rainfall for the four seasons was 7.8 inches. This included 1 dry year and 2 years with above-normal, late-season rainfall. The yield data for these 4 years indicate it is possible to produce a crop in southeastern Arizona using water harvesting. However, one can expect some years with little or no production.

Large cropped areas may give better yields than small areas. If the cropped areas are scattered, they may be susceptible to damage by animals looking for a food source.

Planting on the flat or in small furrows appears preferable to deep furrows or beds. The leveling of the soil in a cropped area can be very critical as low spots will receive more water and give more growth. This could possibly be overcome to some extent by using small

TABLE 6.--Yield of crops harvested and water received by each basin in 1972

Basin	Crop	Yield 1/	Water received 2/
		Lbs/acre	Inches
1	Cantaloupe	4,390	29.0
	Cucumber	12,730	
2	Watermelon	22,110	28.7
	Squash	None	
3	Cantaloupe	9,190	27.2
	Cucumber	7,390	
4	Watermelon	39,950	27.3
	Squash	None	
5	Cantaloupe	6,250	30.6
	Cucumber	26,250	
6	Watermelon	11,550	29.1
	Squash	None	
7	Cantaloupe	10,580	28.9
	Cucumber	10,070	
8	Watermelon	9,390	27.8
	Squash	None	

1/ The zucchini squash were killed by the squash vine borer. The Mexican squash were left to mature for the seed but also had some damage by the squash vine borer.

2/ The rainfall totaled 11.93 inches. After Oct. 1 5.35 inches were received but not multiplied.

furrows for planting. Another factor influencing basin construction is the size and maintenance problem on the levees. Weeds may cause problems as can overtopping and erosion by excessive quantities of water.

The method reported results in crop production, but not every year. It appears to be best suited to small cropped areas.

ACKNOWLEDGMENT

This project was financially supported by the U.S. Water Conservation Laboratory, Phoenix, Ariz.

TABLE 7.--Date and amount of 1973 rainfall measured at the test site

Date	Rainfall
	Inches
July 2	0.11
5	.25
7	.06
14	.08
15	.07
26	.08
27	.02
Aug. 3	.05
4	.03
18	.32
23	.60
Total	1.67

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RUNOFF UTILIZATION FOR GRAIN PRODUCTION 1/

Ordie R. Jones and Victor L. Hauser 2/

INTRODUCTION

Runoff farming in dry regions can increase crop yields by increasing the amount of water available for plant growth (5, 7). Zingg and Hauser (10) developed the Conservation Bench Terrace (CBT) system, which uses most of the principles of runoff farming to conserve and utilize runoff for grain production. The CBT system (fig. 1) uses level contour benches with terrace ridges to control erosion and retain, spread, and infiltrate storm runoff from cultivated contributing areas (watersheds) that are not treated to increase runoff. The CBT system increased grain and forage production on adapted soils at several locations on the Great Plains (1, 3, 4, 6).

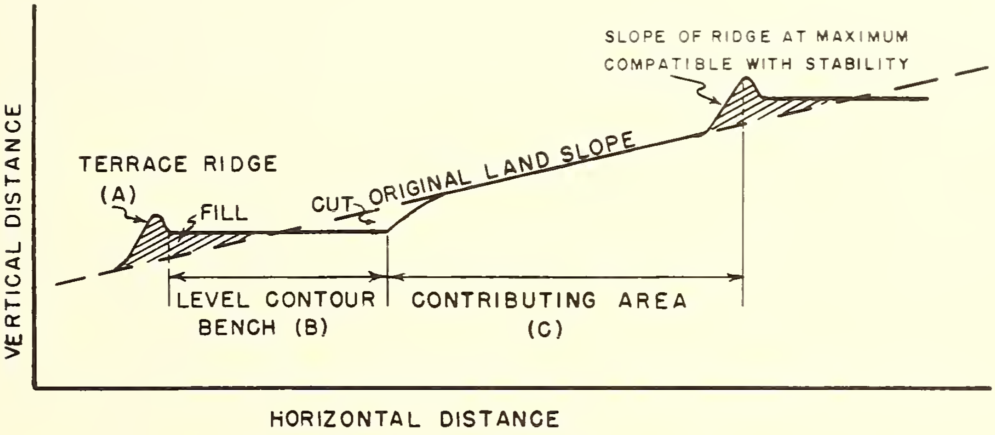

FIGURE 1.--Cross section of a conservation bench terrace. The level contour bench (B) serves as a catchment area for runoff from the contributing area (C). The terrace ridge (A) serves to keep runoff impounded on the bench until it infiltrates the soil.

The first conservation bench terraces were constructed on the Southwestern Great Plains Research Center, Bushland, Tex. (10). This paper reports results of 14 years (1959-72) of research on these

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1/ Contribution from the Soil, Water and Air Sciences, Agricultural Research Service (ARS), U.S. Department of Agriculture (USDA), in cooperation with the Texas Agricultural Experiment Station, Texas A & M University, Bushland.

2/ Soil scientist, Southwestern Great Plains Research Center, ARS, USDA, Bushland, Tex., and Agricultural engineer, Water Quality Management Laboratory, ARS, USDA, Durant, Okla.

terraces, and compares CBT yields with those from other cropping systems to determine the effects of runoff on grain yields.

DESCRIPTION AND PROCEDURE

The climate, topography, and soils at Bushland are typical of dryland areas on the Southern High Plains. Average annual precipitation is 46.6 cm, and average April to September evaporation from a free water surface is 130 cm. The topography is a nearly flat, treeless plain with most natural drainage going into numerous shallow playas. The predominant soil is Pullman clay loam, which holds 26 cm of plant-available soil water in the 0- to 180-cm soil depth. A slowly permeable B soil horizon restricts terminal intake rates to about 0.13 cm/h (8).

A plan view of the experimental area is shown in figure 2. Conservation bench terraces were constructed on a 1.5 percent sloping Pullman clay loam with a watershed to level bench ratio of 2:1. CBT level benches were cropped in continuous grain sorghum (CS), and watersheds were cropped in a wheat-sorghum-fallow (WSF) sequence with at least one watershed in each phase of the sequence every year. The WSF cropping sequence produced one crop of wheat and one crop of grain sorghum in 3 years, with each crop preceded by an 11-month fallow period. Runoff from each treatment in the WSF sequence was measured from graded terraces with 76-cm H-flumes. The amount of runoff contributed to CBT level benches was estimated from runoff measurements on graded terraces.

A level bench was constructed with small dikes on all sides so that no water ran onto or off the bench (4); thus, the only water available for crop production was precipitation that fell on the bench. This bench

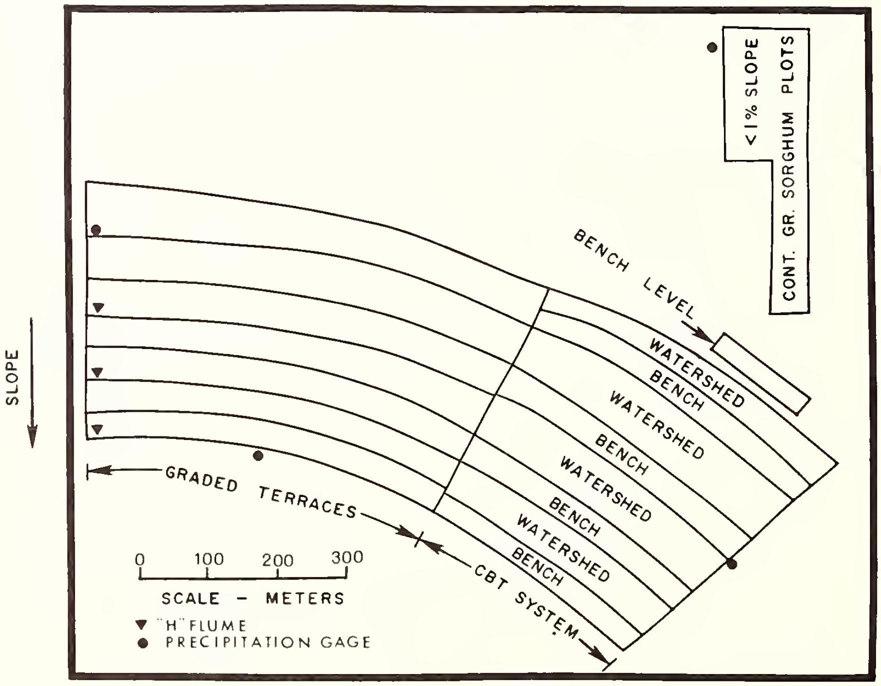

FIGURE 2.--Field plot layout and hydrologic instrumentation for dryland grain production systems.

level treatment, referred to as level bench (NW), no watershed, was cropped in continuous grain sorghum. The effect of runoff contribution on sorghum yields was determined by comparing the sorghum yield on level bench (NW) with yields from CBT level benches.

Continuous grain sorghum was also grown on replicated 0.085-hectare plots with a surface slope of less than 1 percent (9). Runoff from the plots was not measured. By comparing sorghum yields from these plots with yields from the level bench (NW) treatment, the effect of prevention of runoff on grain yields was determined. All yield differences between sloping plots and level bench (NW) treatment may not be attributable to land leveling. The sloping plots were in an experiment separate from the CBT experiment; therefore, cultural practices were not the same. However, we believe that most differences in yield can be attributed to land leveling, and not to other factors.

Stubble mulch tillage was used on all fields and plots to control wind erosion. Nitrogen and phosphorus fertilizer was applied to CBT level benches and the bench level (NW) treatment in amounts required to supply adequate soil fertility on the cut area of the benches (2). The other fields did not require fertilizer.

Soil water contents were determined gravimetrically to the 180-cm depth by 30-cm increments in all fields and plots at planting and harvest. Hybrid grain sorghum was normally seeded in 102-cm rows about June 10 at a rate of 2.2 to 2.8 kg/ha and was harvested in November with a field combine. Yields of grain sorghum on the 0.085-ha plots were determined from hand-harvested subplots. Hard red winter wheat, grown on watersheds and graded terraces, was normally seeded with a drill in late September or early October at a rate of 34 kg/ha and combine-harvested in late June.

RESULTS AND DISCUSSION

Mean monthly precipitation and runoff from graded terraces cropped in a dryland wheat-sorghum-fallow (WSF) sequence for the study period (1959-72) are shown in figure 3. The effect of available soil water content at planting on grain sorghum yields is shown in figure 4 for 14 years of data from CBT level benches, level bench (NW) treatment, sorghum in WSF sequence, and continuous sorghum on a slope. Each centimeter of soil water in excess of 4.5 cm present at planting increased grain sorghum yields 170 kg/ha. The r^2 value of the data indicates that 62 percent of dryland sorghum yield was attributable to soil water content at planting. Unger (9) reported similar results.

Runoff conserved by land leveling increased the amount of water in the soil at sorghum planting (see table 1). For continuously cropped sorghum, the mean soil water content of the level bench (NW) at planting was 1.6 times as great as the soil water content of sloping plots that lost runoff. CBT level benches, which had runon, contained 1.8 times more soil water at planting than sloping plots that lost runoff (table 1). The volume of runoff lost from sloping plots was not measured; however, the 6.5-cm difference between mean soil water content at planting on the level bench (NW) and on sloping plots indicates runoff from the 0.085-ha plots may have been greater than runoff measured from graded terraces.

Comparison of mean grain sorghum yields from the three continuous sorghum treatments shows that differences in soil water content at planting, caused by land leveling, were reflected in grain yields. Runoff prevention on the level bench (NW) and runoff prevention plus runon on the CBT level benches resulted in increased grain yields that were 1.4 and 1.8 times greater, respectively, than yields for plots that lost runoff.

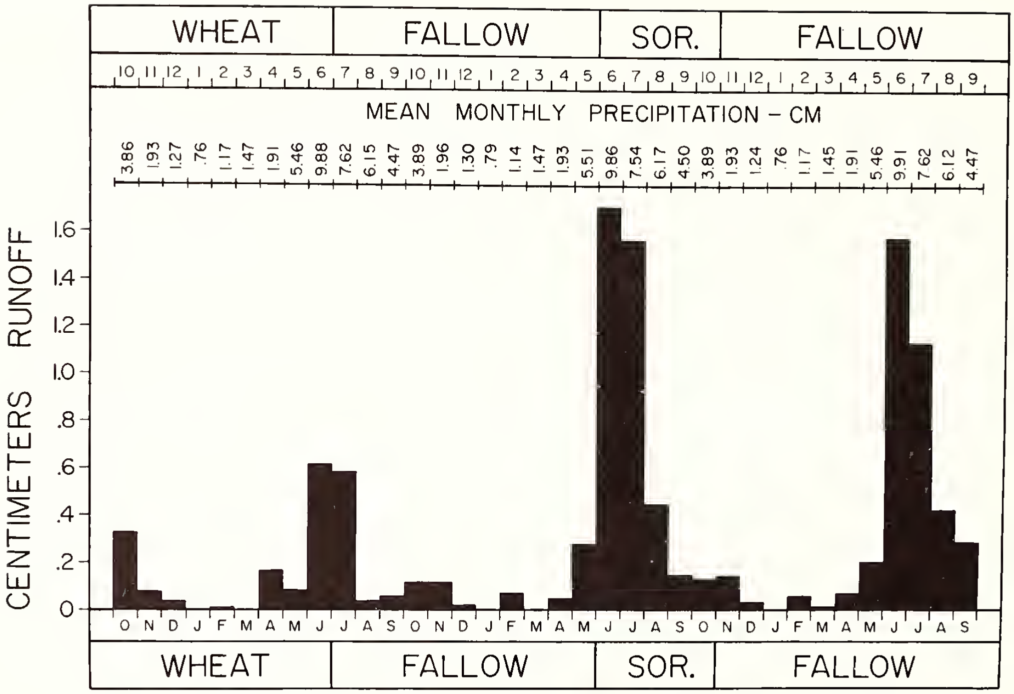

FIGURE 3.--Fourteen-year (1959-72) mean monthly precipitation and runoff from three graded terraces cropped in a 3-year wheat-sorghum-fallow sequence. One terrace was in each phase of the sequence every year.

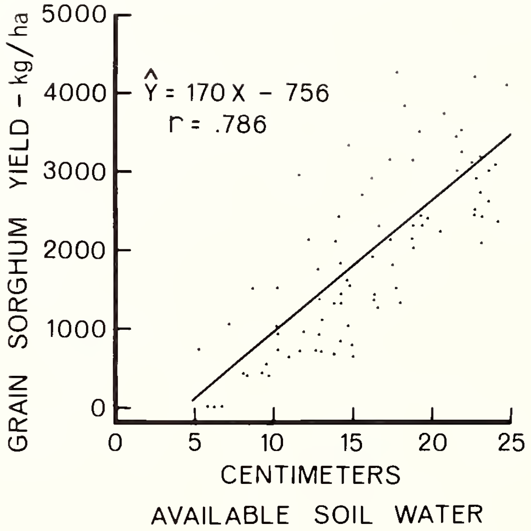

FIGURE 4.--Effect of soil water content at time of planting (0- to 180-cm depth) on yield of dryland grain sorghum (1959-72).

TABLE 1.--Summary of grain yields and water use analyses, 1959-72

Treatment	Mean annual yield Sorghum	Mean annual yield Wheat	Mean runon	Available soil water at planting	Mean water use 1/ efficiency
	Kg/ha	Kg/ha	Cm	Cm	Kg/ha-cm
CBT level bench (CS) 2/:					
Watershed in wheat	3/ 2,180 a		4.01	18.0	
Watershed fallow	2,260 a		8.03	18.0	
Watershed in sorghum	2,260 a		8.81	18.2	
Average	2,230		6.95	18.1	3/ 42.6 a
CBT watershed:					
(WSF) Sorghum	2,010 ab			15.3	30.9 bc
(WSF) Wheat		920			14.3
Level bench (NW), (CS)	1,780 b			16.3	38.1 ab
Sloping plots 4/ (CS)	1,240 c			9.8	29.5 c

1/ Includes fallow periods.

2/ CS = continuous grain sorghum. WSF = wheat-sorghum-fallow cropping sequence. NW = no watershed.

3/ Duncan's Multiple Range Test at 5 percent level of significance. Means followed by the same letters within a column were not significantly different.

4/ Unger (9).

Runon to the CBT level benches (table 1) was estimated to be twice the runoff yield measuered from the WSF sequence on the graded terraces. Although mean annual runon for benches with wheat on the watershed was only one-half of runon for benches with fallow and grain sorghum watersheds, there were no significant differences in mean grain sorghum yields or soil water contents at planting. The lack of yield response to increased runoff indicates that no advantage would be gained by having a watershed to level bench ratio greater than 2:1. Mickelson (6) reported similar findings at Akron, Colo.

Fallowing is commonly practiced in the Great Plains to increase soil water supplies and provide a higher probability for a specified crop yield. However, the CBT level benches and the level bench (NW) treatment had greater soil water contents at the time of sorghum planting with continuous cropping than did sorghum grown in a WSF sequence after 11 months of fallow (table 1). Land leveling may be substituted for fallowing, thus enabling continuous cropping of fields to grain sorghum and possibly to wheat. The mean yield of sorghum after fallow on the watershed was not significantly different from the mean yield on CBT level benches or the level bench (NW) treatment.

The mean water use efficiencies (WUE), shown in table 1, included growing season and fallow period precipitation, soil water changes, runoff, and runon in the analyses. CBT level benches had the highest WUE followed by level bench (NW), sorghum after fallow, and continuous sorghum on a slope. There was very little difference in mean WUE between the last two treatments.

Both conservation bench terraces and bench leveling (level bench, NW) successfully utilized runoff, or potential runoff, to increase grain production. The level bench (NW) system produced more total grain than the CBT system, but annual yield reliability was less and land leveling costs were greater. The probability of producing low sorghum yields (<1,120 kg/ha) was 15 percent on CBT level benches but was 30 percent on the level bench (NW). The probability of high yields (>2,240 kg/ha) was 45 percent on CBT level benches, but was only 28 percent on level benches (NW). Thus, the CBT system increased the reliability of annual crop production. The relative cost of land leveling for the CBT system would be one-third as much as that for leveling all of the field.

Although dryland winter wheat is an important grain crop on the Great Plains, little research has been done on the effects of runoff on wheat yields. This is probably because wheat fields are fallow during many of the summer months when most precipitation and runoff occurs in the Great Plains, thus no crop is growing to utilize stored soil water. Preliminary data from a current study at Bushland show that wheat grown on CBT level benches extracted soil water from deeper in the soil than did grain sorghum. Thus, wheat can be grown on CBT level benches to utilize stored soil water that is unavailable to grain sorghum.

SUMMARY AND CONCLUSIONS

Fourteen years of research have shown that land leveling to control and use runoff water on cultivated fields can greatly increase grain production. Bench leveling to prevent runoff increased mean annual grain sorghum yields 43 percent over yields obtained on sloping plots cropped in continuous sorghum that had runoff. On CBT level benches, which received a mean runoff contribution of 7 cm/yr from watersheds, mean annual grain sorghum yields were 80 percent greater than yields from sloping plots.

The major advantage of bench leveling over the CBT system was that greater farm production was attained because all of the land area was cropped continuously in grain sorghum. A major disadvantage was an increased probability of poor yields (<1,120 kg/ha) on bench level as compared with CBT level benches. A major advantage of the CBT system over the bench level treatment was that only one-third of the cropped area was leveled on the CBT system, whereas all land area was leveled for bench leveling. Both bench leveling and conservation bench terraces adequately controlled wind and water erosion.

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WATER HARVESTING FOR BARLEY IN A 30-CM WINTER RAINFALL AREA 1/

R. E. Luebs and A. E. Laag 2/

INTRODUCTION

A lack of sufficient plant-available water in the root zone during significant periods of the crop growing season is a common occurrence in nonirrigated areas receiving less than 50 cm average annual precipitation. Arable agriculture in areas with 20 to 50 cm of precipitation is commonly termed "dryland agriculture". Dryland crop grain yields are frequently much less than the potential maximum yield because of water stress in the plants. The failure of precipitation distribution to provide adequate available soil water throughout the crop growing season is probably more important than the total annual amount received in low rainfall areas. Luebs and Laag (3) and Luebs (2) have characterized rainfall in southern California with respect to the requirements of dryland grain cropping. High within-season variability in rainfall and an average annual distribution that is out of phase with the crop evapotranspiration season are critical. Grain yield components for barley, one of the few well-adapted dryland crops, are progressively determined throughout the growing season. If any of these yield components--number of culms per unit land area, number of spikes per unit land area, number of kernels per spike, or kernel weight--are limited by water stress in the plants, there will be a permanent limitation on potential grain yield.

Crop and water management systems that conserve water and increase precipitation use efficiency have been investigated widely in dryland areas. Most of these systems were designed to store more water in the soil. The practice of summer fallow has been widely used for this purpose (5). Fallowing land in alternate years has been the standard practice on drylands for 60 years. However, the efficiency of water storage in the potential root zone of the soil by leaving the land lie fallow for a cropping year has been low (4). In southern California, where the coefficient of variation in annual rainfall is extremely high (1), little water would be stored with high fallow storage efficiency in many years because rainfall is so low. A method for utilizing natural runoff from drylands for cropping with a terrace bench system was developed by Zingg and Hauser (8). More recent research with similar objectives was generally discussed by Viets (7) and cited by Luebs and Laag (4). These experimental methods showed promise for increasing precipitation use efficiency and stabilizing production in dryland areas.

Using a portion of the land for the maximum water that can be obtained by runoff has been investigated in an arid area by Myers (6). This technique, called water harvesting, can provide water for livestock. Its experimental use for cropping has been limited, especially in semi-

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1/ Contribution from the Agricultural Research Service (ARS), U.S. Department of Agriculture (USDA); and the California Agricultural Experiment Station.

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arid areas where rainfall is higher. The low and highly variable rainfall area of southern California appeared to be a desirable place to determine the technical feasibility, effectiveness, and limitations of water harvesting on drylands.

METHODS AND PROCEDURE

Field plots with four replications were established on Hanford sandy loam soil near Riverside, Calif. Land slope was 2 to 3 percent. The plots, 7.6 by 15.2 m, were oriented with the long dimension on the contour. The water harvesting system included an area covered with 10-mil black polyethylene film and its adjacent downslope collection area that had been leveled. The combined area was enclosed with an 0.2-m soil dike. In the leveling process, 15 cm of surface soil was removed before leveling and then replaced. The ratio of runoff area to collection area was 1:1. After the first cropping season, when planting was greatly delayed, diversions were constructed at the downslope border of the runoff area to limit water collection on the cropped area if necessary. Check plots and fallow plots were also enclosed in dikes. This report considers only the data obtained in the upslope areas of these plots, where runoff occurred. A detailed report of results concerned with natural runoff control on check and fallow plots has been published (4).

Arivat barley, an adapted dryland variety, was grown. From 10 to 15 kg/ha of phosphorus as treble superphosphate was applied with the seed in all plots. Ammonium nitrate applications were adjusted yearly to water availability, crop observations, and soil nitrate. Average annual applications of nitrogen were 60, 40, and 95 kg/ha for the check, previously fallow, and water harvesting plots, respectively.

Rainfall and amounts of water diverted from the crop plots in the water harvesting system were recorded. Soil water contents and barley yield components were determined during the growing season. Yields of barley grain and straw were obtained.

RESULTS

Rainfall

The trend for lower rainfall during the last half of the barley growing season is shown in table 1. Rainfall from culm elongation to barley maturity averaged 17 percent and ranged from 0 to 35 percent of the total received between crop years. A little less than one-half of the 17 percent occurred from barley anthesis to maturity, a period that averaged 51 days. The average total amount received during this period was 2.6 cm and was usually received in insignificant amounts.

Distribution of rainfall within years varied greatly. In the 1965-66 season, 96 percent or 31 cm occurred before planting; in the 1966-67 season, 51 percent or 17.6 cm was received in the period from emergence to culm elongation; in the 1967-68 season, 46 percent or 11.8 cm occurred before planting; and in the 1968-69 season, 71 percent or 38.4 cm occurred after emergence and before culm elongation. The average annual rainfall, beginning on July 1 and ending June 30, for the 4-year period was 36.6 cm. Rainfall for the 1968-69 season was the fifth highest in 93 years of record at Riverside, 13 km from the experimental site.

Water Harvesting

The water harvesting system, which was designed for collecting rainwater from an area twice that of the cropped area, caused problems of

TABLE 1.--Rainfall and total water retained for barley on one-half the land area with water harvesting

Barley growth periods	Crop year	Period		Rainfall	Retention by water harvesting 1/	
		Dates	Length			
			Days	Cm	Percent	Cm
Previous harvest to planting	1965-66	6/17-2/15	243	31.0	97	60.1
	1966-67	6/6-11/15	162	4.4	100	8.8
	1967-68	5/25-12/5	194	11.8	62	14.6
	1968-69	5/16-1/3	232	8.8	82	14.4
Planting to emergence	1965-66	2/15-2/27	12	.0	0	.0
	1966-67	11/15-11/25	10	.1	100	.2
	1967-68	12/5-12/26	21	3.2	34	2.2
	1968-69	1/3-1/15	12	3.6	50	3.6
Emergence to culm elongation	1965-66	2/27-4/8	40	1.3	100	2.6
	1966-67	11/25-1/27	61	17.6	65	22.9
	1967-68	12/26-2/14	50	3.7	81	5.7
	1968-69	1/15-3/17	61	38.4	12	9.1
Culm elongation to anthesis	1965-66	4/8-5/5	27	.0	0	.0
	1966-67	1/27-3/17	49	5.9	100	11.8
	1967-68	2/14-3/20	35	4.3	100	9.6
	1968-69	3/17-4/12	26	1.8	100	3.6
Anthesis to maturity	1965-66	5/5-6/6	32	.0	0	.0
	1966-67	3/17-5/25	69	6.1	100	12.2
	1967-68	3/20-5/16	57	2.8	100	5.6
	1968-69	4/12-5/29	47	1.5	100	3.0
Total or average	1965-66			32.3	97	62.7
	1966-67			34.1	82	55.9
	1967-68			25.8	73	37.7
	1968-69			54.1	31	33.7

1/ Based on twice the rainfall, that is, rain on cropped plot plus that on an equal-sized and covered runoff plot.

excess water, particularly during the first half of the barley growing season. As a consequence, and because the 1965-66 planting was greatly delayed beyond the optimum date, wooden diversions were constructed at the downslope edge of the runoff plots before the 1966-67 season. Thereafter, water was diverted from the plot area when there was a high probability of it being deleterious to the crop. In 2 of the 4 years, significant water was diverted before planting (table 1). During these years, no additional water was harvested from rainfall occurring between November 15 and the planting date if the seedbed was sufficiently moist for germination. This was necessary so that the soil was not excessively wet for planting during the most optimum period.

Excessive water with the water harvesting system was especially deleterious during the 10- to 20-day period between planting and emergence. Standing water on the plots followed by drying resulted in a surface soil crust that effectively prevented emergence of the barley seedling. As a consequence, during the 2 years when rainfall occurred between planting and emergence no water was harvested (table 1). High rainfall during the emergence to culm elongation period also prevented the harvesting of all water falling on the covered area. Much of this rainfall occurred early in the period when inundation of the small barley seedlings could be tolerated only for a short time. One characteristic of rainfall patterns in southern California that can result in short-term excesses of rainwater on land is the high probability of closely spaced succeeding rainfall events after the first has occurred. For example, measurable rainfall was recorded during 36 of the 61 days between emergence and culm elongation in 1969. This rainfall pattern is less probable later in the season, and with lesser amounts per event all the water falling on covered plots was harvested.

The tendency for a series of closely spaced rainfall events to occur after the first occurs, as well as for a relatively long dry period after clearing weather, has usually been a problem in dryland field operations. The length of the growing season and the dates for the growing stages are greatly dependent on the date of planting. The latter was dependent (1) on the first occurrence of a rainfall event in excess of 1 cm after November 15 and (2) on an interval between events of sufficient time to complete the seedbed preparation and plant. Data on soil water storage, yield components, and crop yield for 1966 are not presented because barley planting with the water harvesting system was delayed 1 month beyond the planting date for the check and previously fallowed plots. Planting dates were the same for the remaining 3 years of the study. Yellow dwarf disease of barley was observed during the 1967 and 1968 crop years. The severity of infection tended to be greatest in water harvesting plots, presumably because of wetter conditions. Barley was sprayed with an insecticide to control aphids, which are vectors for the disease. The effect of this disease on crop yeild was considered to be minimal.

Available Soil Water

Water harvesting increased the available soil water throughout the barley growing season (table 2). The 3-year average values and the yearly range of values were higher than for the check plots and for the fallow-crop plots. The latter system requires the same land area as the water harvesting system used and is the dominant dryland cropping system used in California.

Increased water in the 0- to 90-cm soil depth at crop emergence was one-third greater for water harvesting over the check. At culm elongation, this increase was 100 percent. Available water amounts in previously fallowed plots were intermediate. By anthesis, when the crop had developed its maximum transpiring surface and meteorological factors favored high transpiration, there was considerable available soil water where water was harvested, but it was nearly exhausted in the root zone of check plots and previously fallowed plots.

Data showed that water harvesting stored an average of over 4 cm available water in the 90- to 180-cm soil depth from crop emergence to anthesis, whereas no more than 1 cm was shown at this depth in the check plots. As was expected, fallowing the land the previous year increased water storage in the 90- to 180-cm depth. However, the level of available water at anthesis was one-half that obtained with water harvesting. The increased available soil water resulting from water harvesting was evident at crop maturity and averaged 2 cm for the 0- to 180-cm soil depth. In the check plots where barley was grown the previous year and where the land was fallowed the previous year, available water had been exhausted by maturity.

TABLE 2.--Available soil water at barley growth stages with water harvesting and other cropping systems (1967-69) 1/

Growth stage	Soil depth	Check		Water harvesting		Fallow-crop	
		3-year average	range	3-year average	Range	3-year average	Range
	Cm	Cm	Cm	Cm	Cm	Cm	Cm
Emergence	0-90	6	1-8	8	4-10	7	4-9
	90-180	1	1-1	5	4-7	4	3-5
Culm Elongation	0-90	4	2-7	8	5-9	5	3-8
	90-180	1	1-2	6	5-6	4	3-5
Anthesis	0-90	<1	<1-<1	4	3-6	1	<1-1
	90-180	1	<1-3	4	4-4	2	1-2
Maturity	0-90	<1	<1-<1	1	<1-1	<1	<1-<1
	90-180	<1	<1-<1	1	<1-2	<1	<1-<1

1/ Water held at tensions less than 15 bars.

Nitrogen deficiency of the barley in the water harvesting plots was apparent early in the 1967 growing season. Plants were analyzed at the late tillering stage for total nitrogen. Plants in the water harvesting plots contained 2.9 percent nitrogen compared with 4.7 percent for plants in the check plots and 5.1 percent for plants in the previously fallowed plots. This nitrogen deficiency early in the growing season could have resulted from less nitrification in wetter and coler surface soils and some leaching of nitrate. Leaching was suggested by higher soil nitrates in the 60- to 120-cm depth of soil with water harvesting, an average of 7.4 parts per million NO_3-N compared with 2.3 p/m for the check. The need for application of nitrogen fertilizer at planting for barley grown on a sandy loam soil with a water harvesting system was apparent. Overall greater application of nitrogen also appeared to be necessary to efficiently use the additional water made available by water harvesting.

Generally, high yield component values were measured for barley grown with the water harvesting system (table 3). The number of spikes per meter of row, number of kernels per spike, and the kernel weight were much higher for water harvesting than for the check. This reflects the additional soil water available throughout the crop growing season. The high culm density for check plots resulted from excessive secondary tillering in 1967 when water became available to plants that had previously undergone extreme water stress. Spike density and kernels per spike for barley after fallow were slightly higher than for the check. Greater water storage after fallow along with fewer kernels per spike resulted in an average kernel weight equivalent to that for water harvesting and 29 percent higher than the check.

Barley grain yields were consistently doubled by water harvesting on the basis of area cropped (table 4). However, because twice the total land area was used for water harvesting, smaller yield increases were obtained with water harvesting in 2 of 3 years on a total area basis. A maximum increase of 420 kg/ha was measured in 1967. Yields with water harvesting were also higher than after fallow where land

TABLE 3.--Grain-yield components with water harvesting and common cropping systems (3-year average, 1967-69)

Management system	Yield components			
	Culms	Spikes	Kernels	Kernel weight
	No./meter of row		No./spike	Mg.
Check	1/ 78	53	17	28
Water harvesting	72	67	25	36
Fallow-crop	70	56	20	36

1/ Culm density in 1967 was twice that in 1968 and 1969.

TABLE 4.--Barley grain and straw yield of cropped areas with water harvesting and other cropping systems 1/

Year	Check		Water harvesting		Fallow-crop	
	Grain	Straw	Grain	Straw	Grain	Straw
	Metric ton/ha					
1967	2/ 0.62a	4.47a	1.66c	8.65b	1.61bc	9.47b
1968	1.06a	3.54a	2.03c	5.43b	1.71b	5.15b
1969	1.50a	4.34a	3.19c	5.26a	2.05ab	5.81b
Average	1.06	3.99	2.29	6.45	1.79	6.81

1/ Check required one-half the land area of the other 2 systems.

2/ Mean followed by a letter is significantly different at the 5-percent level from mean not followed by that letter within any 1 year.

area used was the same. Statistically significant differences were obtained in 2 of the 3 years. The 3-year average yield increase for water harvesting over fallow was 28 percent or 360 kg/ha.

Straw yields, which are an indication of forage production potential, were similar with water harvesting and the fallow system and consistently higher than for the check on a planted area basis. The average increase over the check was 71 and 62 percent for after fallow and with water harvesting, respectively. Straw yields with water harvesting and the fallow-crop system were from 3 to 4 metric tons higher in 1967 than other years. An earlier planting date (table 1) combined with more available soil water and possibly more residual available nitrogen may account for this. This was the only year of three that water harvesting and previous fallow produced as much or more straw as the check on a total area basis. During the other 2 years, the straw yield from check plots averaged about 2.5 tons/ha more.

DISCUSSION

While water harvesting consistently and markedly increased available water in the root zone, increases in barley grain production were significant in only 1 of 3 years. An analysis of other data obtained in the same field study showed that retaining most of the natural runoff on land and cropping annually resulted in a higher rainfall use efficiency than did water harvesting (4). However, it appears that an improved design for water harvesting in the climatic area and on the soil under consideration could lead to higher rainfall use efficiency. Inasmuch as an average of only 62 percent of the potential water was retained on the cropped plots with water harvesting during the 3 years of satisfactory crop management, a 25- to 50-percent reduction in the runoff area appears feasible. The resulting reduction in water harvested would presumably provide a reasonably adequate supply for the crop and the smaller runoff area would result in increased land area for crop production.

Water harvesting can easily result in excessive water on the land (1) when final seedbed preparation and planting is imminent and (2) between planting and emergence. These are critical periods because in many years a 2- to 3-week delay in planting date reduces yield potential. It is doubtful if reducing the runoff area will greatly ameliorate this problem, and diversion of runoff water from the area to be cropped would therefore be required.

Increasing the available nitrogen for the crop was found to be a requirement of the water harvesting system. Early season availability of nitrates apparently was less because of the wetter surface soil as well as leaching. As with irrigation, optimum crop growth for efficient use of water from water harvesting requires that nitrogen fertilizer be applied. This would preferably be done at planting or during the first one-third of the crop growing season.

Finer textured soils with a higher water holding capacity than the sandy loam in this study may have maintained a higher soil water availability in the root zone between rainy periods and reduced downward water movement below the root zone. However, an effect of finer texture to reduce infiltration would increase the likelihood of excessive surface water for the crop.

Water harvesting continues to merit experimental consideration for making more variable winter rainfall. Reducing the cost of sealing the surface of the runoff area, optimizing the ratio of runoff to collection area, and using higher value or higher producing crops need research emphasis to determine if water harvesting is practicable where annual rainfall is 30 cm or greater.

SUMMARY

A water harvesting system was used for barley production in a 30-cm winter rainfall area on sandy loam soil. The runoff area to collection area ratio was 1:1, and the runoff area was covered with polyethylene film. Control of the runoff water was necessary, and an annual average of 62 percent of the maximum possible was retained on cropped areas. Available soil water was increased throughout the crop growing season with water harvesting. Barley grain production was increased significantly in 1 year of 3. Production with water harvesting was greater 2 of 3 years when compared with the fallow-crop system, which used the same land area. Additional research with water harvesting will be required before its practical use on drylands receiving 30 cm or more annual rainfall can be established.

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DISCUSSION

SESSION IV, Part 2--Richard Frevert, Chairman

L. HERMSMEIER: Why was clear plastic used rather than black plastic in water harvesting basins?

J. HOOVER: The selection of the color of plastic is dependent upon the amount of contact expected with the soil. Black plastic exposed to full sunlight may get as hot as 150° F. If this black plastic is separated from the soil by an airspace, the soil temperature may be only a little warmer than that of uncovered soil, but if it makes good contact, the soil temperature will approach that of the black energy absorbing cover. Clear plastic permits solar energy to be transmitted through the film and is absorbed by the soil. In this case, the color of the soil then determines how much heat is built up under the cover, and not the amount of contact with the soil. It was felt that the clear plastic cover would not modify the soil environment as much as the black plastic cover. Hence, I chose the clear plastic for sealant cover on the field plots at Madison, S. Dak.

SESSION V--Ron Reeve, Chairman

OPPORTUNITY FOR HARVESTING WATER FROM AND ALONG HIGHWAYS IN RANGELAND AREAS OF WYOMING [1]

C. E. Evans, D. A. Woolhiser, and Frank Rauzi [2]

INTRODUCTION

As one drives along the highways traversing Wyoming's extensive semiarid rangelands, one frequently notices a striking difference between the vegetation growing along the highway and that growing outside of the fenced rights-of-way. This contrast is caused by differential grazing and/or runoff from highway surfaces being utilized for improved plant growth. Perhaps these resources (land and water) could be better utilized by harvesting water from the highways and conveying it to storage or diverting it to adjacent lands. This runoff could be used for livestock water, supplemental irrigation for increased forage production, or for enhancing shrubs and vegetation for beautification or recreational purposes, wildlife habitat, or for a combination of these and other uses.

EVALUATION OF WATER HARVESTING OPPORTUNITY

Preliminary Evaluation

A preliminary evaluation of the potential for water harvesting from highways was made for the North Platte Basin in southeastern Wyoming. If we assume 95 percent runoff from highways during the 4 months, May to August, a mean water supply of approximately 3,100 acre-ft would be available from 5,800 acres of paved two- and four-lane highways. Although this quantity is only 0.2 percent of the water diverted for irrigation in the basin, its efficiency of use may be considerably higher than much of the water currently diverted for irrigation purposes. Additional water for livestock or for hay production could mean a great deal to ranches on upland watersheds where water is presently not available or is very expensive to obtain.

Analytic Methods

For a more realistic appraisal of water supply from pavement, we must consider precipitation as a stochastic process. A general stochastic model of daily precipitation, which has many attractive features for studies of this sort, has been presented by Todorovic and Woolhiser (4). They also considered a special case of the general model in which the occurrence of rainfall is specified by a Markov Chain and the distribution function of daily rainfall is negative-exponential. The temporal and spatial variation of the parameters was considered by Woolhiser, Rovey, and Todorovic (6). This model was called the Markov Chain-Exponential (MCE) model. The distribution function of the total rainfall in n days is

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[1] Contributions from Agricultural Research Service (ARS), U.S. Department of Agriculture (USDA), in cooperation with the Colorado State University Experiment Station, the University of Wyoming Experiment Station, and the Wyoming Highway Department.

[2] Area Director, Colorado-Wyoming; research hydraulic engineer, Fort Collins, Colo.; and soil scientist, Laramie, Wyo.; respectively, ARS, USDA.

$$F_n(x) = \{(1 - q_0) - Rd\}\ (1 - q_0)^{n-1}$$

$$+ \sum_{\nu=1}^{n} \{R\ \phi_1(\nu,n) + (1-R)\ \phi_0(\nu,n)\ \frac{\lambda^{\nu}}{\Gamma(\nu)} \int_0^x u^{\nu-1}\ e^{-\lambda u}\ du \qquad (1)$$

where q_0 is the probability of a dry day being followed by a wet day; x is the total depth of rainfall in n days; R is the probability that the day before the period begins is wet; $d = q_1 - q_0$ where q_1 is the probability of a wet day being followed by a wet day; $\phi_1(\nu,n)$ is the probability that ν wet days occur in an n-day period given the day before the n day period is wet; $\phi_0(\nu,n)$ is the probability of ν wet days in n days given the day before the n-day period is dry; λ is the parameter in the negative exponential distribution for daily rainfall; Γ denotes the gamma function; and u is a dummy variable. The analytic expressions for $\phi_0(\nu,n)$ and $\phi_1(\nu,n)$ are presented in Todorovic and Woolhiser (4).

Although equation 1 is complicated, it can be evaluated readily with a digital computer. Because it is based on a logical probablistic model of daily rainfall occurrences, other distribution functions can be derived that depend on the same parameters. If we assume that T inches of rain will be retained on a highway surface on each rainy day and that the remainder will run off, it can be shown that the distribution function for the total runoff in an n-day period will be the same as equation 1 except that the parameters, q_0, q_1, and R will be replaced by q_{0T}, q_{1T}, and R_T where

$$q_{0T} = \frac{e^{-\lambda T}[q_0(1 - q_1) + q_0 q_1(1 - e^{-\lambda T})]}{[1 - q_1 + q_0\ (1 - e^{-\lambda T})]} \qquad (2)$$

$$q_{1T} = q_1 e^{-\lambda T} \qquad (3)$$

$$R_T = R\ e^{-\lambda T} \qquad (4)$$

Distribution functions of 14-day rainfall and 14-day runoff with a threshold T = 0.05 inch are shown in figure 1 for two periods at Gillette, Wyo. These distributions given an indication of the variability of the water supply. For example, the runoff from a paved surface would be less than 0.5 inch in approximately one year out of five during the 2-week period beginning May 24, and would be zero in approximately one year out of five during the 2-week period beginning July 19. The above rainfall model can also be utilized very effectively in simulation studies for storage design (2).

Simulation Techniques

Runoff from highways could be utilized in two ways, as supplemental irrigation water: (1) flood irrigation of the embankment form highway runoff, and (2) conveyance of highway runoff to leveled areas.

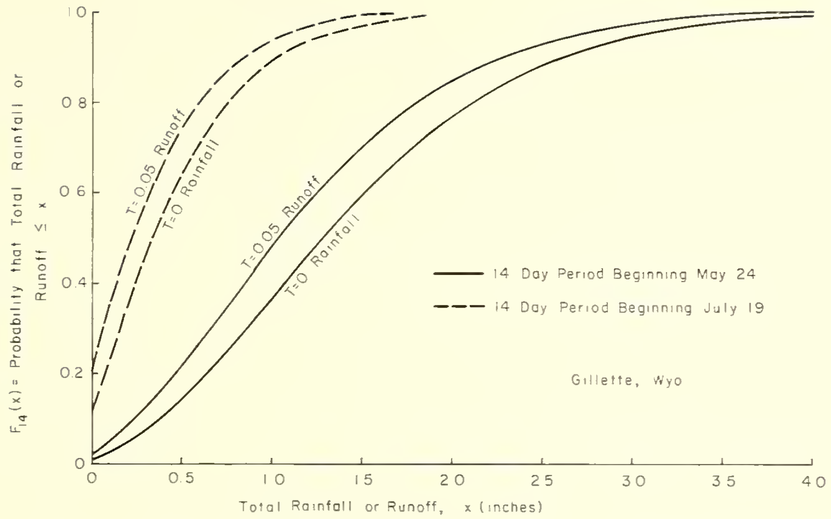


FIGURE 1.--Distribution functions of 14-day rainfall with and without a threshold.

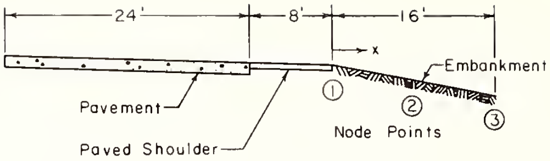
Case 1

The first case can be investigated by using presently available hydrologic models. A typical interstate highway section is shown in figure 2a. Overland flow from the highway and a vegetated embankment was modeled by the kinematic cascade (5) and infiltration on the embankment by a method presented by Smith (3). Infiltration parameters were estimated for two soils, Maysdorf fine sandy loam and Renohill clay loam, using infiltrometer data obtained by Rauzi (unpublished data).

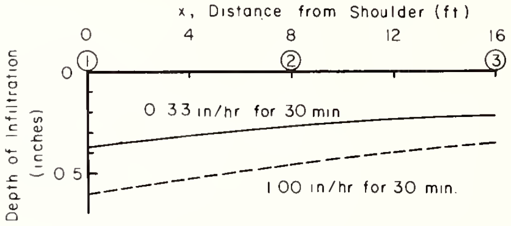
The amounts of water infiltrated at points 1, 2, and 3 on the embankment for two different rainfall inputs are shown in figures 2b and 2c. If all of the water had been infiltrated on the embankment and all had run off the highway and shoulders, 0.50 inch would have infiltrated for the 0.33 in/h rate and 1.50 inches for the 1 in/h rate. It can be seen from the figure that some water ran off the embankment for both storms for both soil types. However, approximately the same amounts infiltrated into both soils for the 0.33 in/h rate while the Maysdorf soil absorbed significantly more water from the higher intensity storm. This example shows that water running off highways will add very little to the soil water in embankments when the rainfall intensity is great enough to cause runoff from the embankment. Therefore, more water will be infiltrated into the embankment of the sandy loam than the clay loam soil. Simulations such as these, using natural rainfall intensity patterns, could be used to evaluate the effectiveness of highway runoff as a source of additional water for growing vegetation on embankments.

Case 2

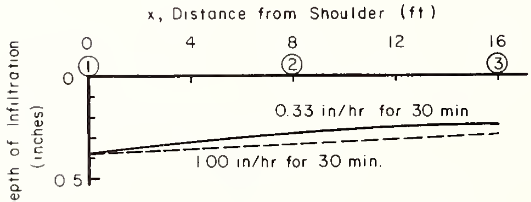
Consider the definition sketch of figure 3. A highway surface area A_1, contributes runoff to area A_2, which also receives natural rainfall, x_1. The amount of water, z, per unit of area received by A_2 is



(a) Typical Interstate Highway Section



(b) Depth of Infiltration on the Embankment
Maysdorf Fine Sandy Loam



(c) Depth of Infiltration on the Embankment
Renohill Clay Loam

FIGURE 2.--Infiltration on highway embankments.

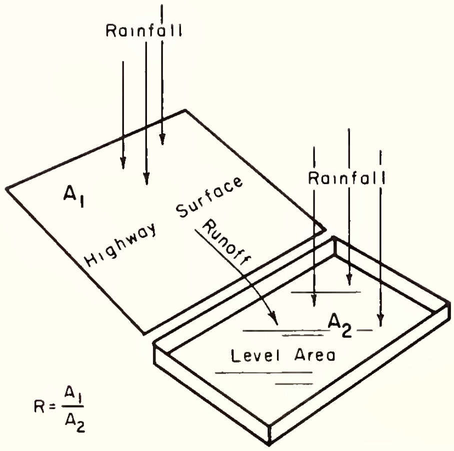


FIGURE 3.--Definition sketch of water harvesting system.

$$\left.\begin{array}{l} z = x_1 \quad \text{if} \quad x_1 \leq T \\ \\ z = x_1 + r(x_1 - T) \ \text{if} \ x_1 > T \end{array}\right\} \qquad (5)$$

where $r = A_1/A_2$ and T is the runoff threshold.

The distribution function of total water applied to area A_2 is

$$\left.\begin{array}{ll} F(z) = 1 - e^{-\lambda z} & ; \quad z \leq T \\ F(z) + 1 = e^{-\frac{\lambda}{(r+1)}(z+rT)} & ; \quad z > T \end{array}\right\} \qquad (6)$$

Although this function could be used to develop an analytic expression similar to equation 1 for the total input to the area A_2 in n days, the expression would be extremely cumbersome. Therefore, simulation techniques were used to obtain sample function of soil water content and distribution functions of the relative soil water content under natural rainfall conditions with two contributing area ratios, r = 1 and r = 2. The runoff threshold chosen was T = 0.5 inch. (See figs. 4 and 5.) The maximum effective water holding capacity for the top 2 feet of the Maysdorf fine sandy loam was assumed to be the water content at one-third atmosphere, ST2; the minimum was the water content at the wilting point, which was obtained from field observation, Q2. Evapotranspiration was modeled using an adaptation of a model developed by Hanson (1) with parameters calibrated for Gillette lysimeter data.

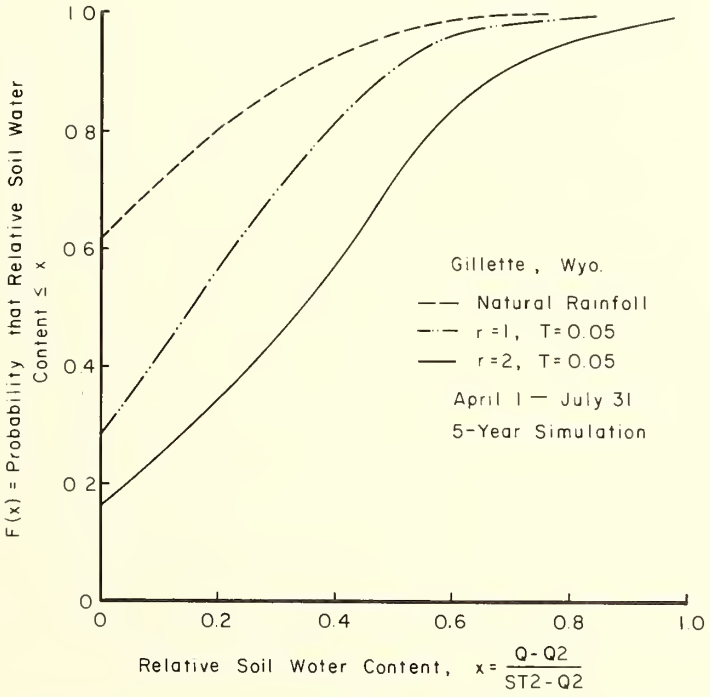


FIGURE 4.--Distribution functions of relative soil water content.

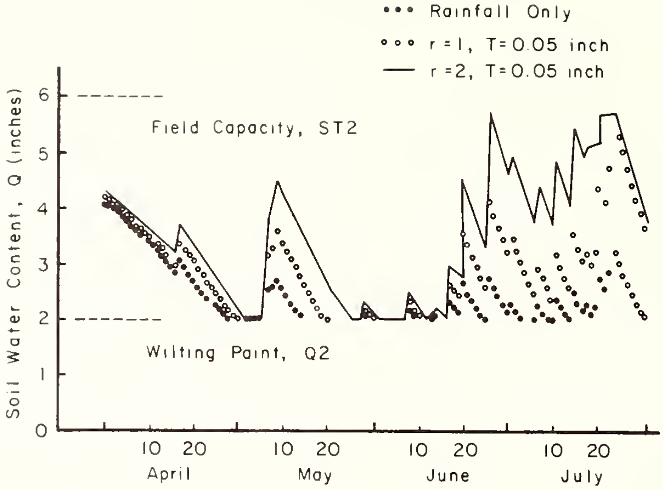


FIGURE 5.--Simulated soil water content of top 2 feet of soil, Gillette, Wyo., April-July 31.

An examination of figures 4 and 5 shows that water contributed from the highway does not prevent the soil water content in the top 2 feet from reaching the wilting point; however, it does reduce the amount of time the soil water content is at the wilting point. Unless storage facilities are provided, it appears that there is a limit below which the probability of wilting cannot be reduced by increasing the size of the contributing area. This limit exists because of the finite capacity for storage of water in the top 2 feet of soil. Once this zone has reached field capacity, any additional water added will go to deep percolation. This probability is a function of the water holding capacity of the soil, the evapotranspiration rate, the rainfall process, and the area ratio, r. It might be a useful indicator of the suitability of a crop or species to the modified soil-water environment. The effect of these water regimes on plant growth requires field evaluation. A plant growth model would also be useful in evaluating the potential of water harvesting from highways for crop growth.

FORAGE YIELD OBSERVATIONS ALONG HIGHWAYS

Forage yield observations along the rights-of-way of Interstate Highway 90, west of Gillette, in northeastern Wyoming, showed substantially greater production than was observed from adjacent native rangelands. These differences in herbage production show the beneficial effects that the highway runoff water has on the vegetation of the rights-of-way. The rangelands contiguous to the highway receive only natural precipitation amounting to 10 to 14 in/yr, of which approximately 25 percent occurs as snow in the winter months. Nordan crested wheatgrass and yellow blossom sweet clover are the predominating species in the medians and borrow areas, having been seeded in accordance with specifications of the Wyoming Highway Department.

Considerable acreages are involved in the total highway complex. The pavement of Interstate Highway 90 occupies 8 acres/mi, narrow medians comprise 3 to 4 acres, wide medians about 15 acres, and borrow areas make up the largest acreage, averaging from 23 to 31 acres/mi, depending upon the width of medians and rights-of-way. The major soil type in this area is Renohill clay loam. During the construction of the interstate highway, soil from various depths was mixed and compacted; hence, the soil of the disturbed area bears little resemblance to the rangeland soil.

During the first week of July 1973, approximately 9 miles of the medians and borrow areas of Interstate 90 west of Gillette were harvested. Samples of hay bales weighed a few days after harvest showed an average weight of 55 lb/bale. Hay yields were computed to be 1.3 tons/mi of narrow median (0.37 tons/acre) and 2.8 tons/mi of wide median (0.9 tons/acre). Because of the variability of the topography, it was difficult to obtain a good estimate of forage yield from borrow areas. Estimates ranged from 3 to 8 tons/mi of highway (0.11 to 0.30 tons/acre). Thus, harvest under these conditions could be as high as 12 tons of quality hay per mile.

DISCUSSION

Exploratory studies of the water harvesting potentialities of sections of interstate highways in Wyoming have been initiated to determine the amounts of water available for harvest and the value of the water for livestock or for producing herbage on median strips and along the borrow areas of rights-of-way. Although a limited number of stock water ponds along interstate highways are fed by runoff from the pavements and many ranchers harvest the herbage from the borrow areas along highways near their operations, much of the water resource is wasted. Too often, runoff from highways is consumed by grasses and weeds that are difficult to harvest, percolates beyond the reach of vegetation in borrow pits, or collects in depressions and evaporates leaving unsightly and vegetation-damaging accumulations of salt along the rights-of-way.

A preliminary evaluation of the potential for water harvesting from highways in the North Platte Basin in southeastern Wyoming indicated a mean water supply during the 4 summer months of only 3,100 acre-ft from 5,800 acres of paved two- and four-lane highways. Although this quantity is only 0.2 percent of the water diverted for irrigation in the basin, and as such could not have a profound effect on the region's economy, the additional water for livestock or as a reliable source for hay production could stabilize the ranching operations on upland watersheds where water is not now available or is too expensive to obtain.

The variability of water supply from pavements was demonstrated using a stochastic model based on daily summer percipitation near Gillette. This appraisal showed runoff from paved surfaces to be less than 0.5 inch in one year out of five for the 2-week period beginning May 24 and zero in one year out of five for the 2-week period beginning July 19. Storage facilities would necessarily have to be provided if runoff from highways is to be utilized for livestock water. Stochastic rainfall models can be used in simulation studies to determine the amount of storage required to utilize highway runoff for livestock water supplies. They can also be used in conjunction with infiltration and surface runoff models to give a preliminary evaluation of the effectiveness of highway runoff as a source of additional water for plant growth on highway embankments or on leveled areas. Although some additional field data will be required to see if the parameters used in the simulations are reasonable, the simulation results are helpful in planning field research and will add to the value of short-term field data.

Various mixtures of native and introduced grasses with a legume have been seeded in the median and borrow areas along highways. In the Northern Great Plains, Nordan crested wheatgrass is used extensively. When crested wheatgrass is used in a mixture, it soon becomes dominant because of its aggressiveness and early growth. Yellow blossom sweet clover, a biannual, is often seeded because of its adaptability to a variety of sites. Although the Wyoming Highway Department does not recommend alfalfa in the seeding mixtures, it occurs widely along highway rights-of-way, undoubtedly as a result of foreign seed being scattered from vehicles. Once established, the alfalfa persists. In Wyoming, a thick layer of topsoil is usually spread over the raw soil before seeding. Surfaces are generally mulched with straw at 2 tons/acre and fertilized with 40 lb of N per acre.

As reported in the previous section, forage production along highways is highly variable and much of the growth produced is not, or cannot be, harvested for hay. On the more productive areas, as much as 12 tons of quality hay per mile of highway are being harvested. With proper fertilization, land leveling and shaping, better adapted plant species, and improved management, together with more effective use of the water harvested from paved surfaces, yields of herbage probably could be increased substantially. However, additional research data are needed to determine the magnitude of potential increases in herbage production.

In semiarid climates, like those prevailing on most of Wyoming's extensive rangelands, the land required for highway rights-of-way has only limited value in itself. Its greatest value can be the water that falls on it year after year. The precipitation that falls on the highway rights-of-way might be harvested and conveyed to adjacent lands for beneficial uses. These uses may include supplying water for livestock, irrigating forages, producing shrubs and vegetation for recreational purposes, growing habitats for wildlife, providing vegetation for beautification, or a combination of these or other uses.

ACKNOWLEDGMENTS

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ESTABLISHING WINDBREAKS IN SEMIARID AREAS BY ALTERING THE MICROCLIMATE OR SUPPLYING ADDITIONAL WATER [1]

J. D. Dickerson and N. P. Woodruff [2]

ABSTRACT

Seven methods were used to supply additional water or alter the microclimate of redcedar (*Juniperus virginiana*) and Scotch pine (*Pinus sylvestris*) trees to induce faster growth and higher survival rates. For redcedars, two water-harvest treatments produced 32 and 31 percent more total growth than did a control, while drip irrigation and snow-fence-protected treatments produced 25 and 24 percent more total growth, respectively. Shaded treatment did not increase redcedar growth but resulted in 100 percent survival as compared with 70 percent for the control.

Although Scotch pines had discouraging growth and survival rates, they tended to have better survival and total growth in a protected or shaded environment.

INTRODUCTION

Trees planted in rows to protect fields, farmsteads, animals, and humans from winds are a valuable asset (2, 4, 7, 29, 31, 33, 36). Such tree barriers have been studied for their influence on wind erosion, microclimate, human and animal comfort, and other beneficial uses. Trees planted as barriers in areas of low annual rainfall and poor soil-physical characteristics generally grow slowly and erratically (9, 11, 27). Therefore, we initiated a study in an area of limited rainfall to find a simple, productive method of increasing tree growth and survival.

Numerous publications are available on rainfall multiplication techniques for obtaining water for agricultural production, livestock, and humans (8, 15, 22, 24, 25, 26, 28, 34); use of gravel mulches to reduce evaporation and enhance infiltration (1, 14); use of wind barriers to modify microclimate and trap snow for the benefit of vegetation and livestock (4, 5, 12, 13, 20, 29, 33, 35); solar stills for obtaining water in desert areas (16, 17, 21); profile modification to improve physical conditions of soils (10, 18, 19, 32); and effect of solar radiation and shading on evapotranspiration, crops, and animals (3, 6, 23, 30). We evaluated many techniques mentioned (water harvesting, mulches, and so forth) to determine their application for increasing growth and survival of trees in arid and semiarid regions.

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[1] Contribution from the Agricultural Research Service (ARS), U.S. Department of Agriculture (USDA), in cooperation with the Kansas Agricultural Experiment Station, Department of Agronomy Contribution No. 1402.

[2] Agricultural engineer and Research Leader, respectively, ARS, USDA, Manhattan, Kans.

DESIGN AND DESCRIPTION OF EXPERIMENT

At the Colby Agricultural Experiment Station, Colby, Kans., we planted the first trees in April 1971. The soil at the site is a silty clay loam, 15 percent sand, 54 percent silt, and 31 percent clay. Mean annual rainfall for the area is 19 inches.

Seven treatments and a control were selected for the initial experimental design. Each treatment was replicated twice. The seven treatments were (1) water-harvest area 50 by 100 feet, (2) water-harvest area 50 by 50 feet, (3) partial shading, (4) snowfence protection, (5) solar still, (6) profile modification, and (7) gravel mulch.

The trees were planted within a 3-acre plot in 50-foot rows with a 5-foot spacing between each tree. Half of each row was planted to redcedar (*Juniperus virginiana*); the other half, to Scotch pine (*Pinus sylvestris*). The trees were measured at the beginning and end of the growing season, and the difference between the two measurements was the growth for that year; the sum of all the differences was total growth. Trees that did not survive were replanted at the beginning of each season.

The water-harvest areas were cleared, smoothed, and bermed around the edges to pond runoff on the tree row. Three materials, (1) 6 mil polyethylene, (2) asphalt emulsion, (3) silicone and latex-in-water, were used to cover the water-harvest areas--one for each successive year. We modified the soil profile by digging a trench 2 feet wide and 4 feet deep along the length of the row and then mixing the soil and refilling the trench. The solar stills--a trench 3 feet wide by 4 feet deep by 50 feet long covered with 1 mil Tedlar--were located adjacent to the tree row; water collected in a partitioned trough was piped to each individual tree. A check valve was fabricated from a funnel, table-tennis ball, and wire mesh to allow rainwater to flow into the trench and not collect on the Tedlar cover. For partial shading, we covered the tree row with a 50-foot length of snowfence supported by steel posts. The barrier-protected areas were surrounded with 60-percent porous snowfencing, 48 inches tall, located 25 feet from the row laterally.

Tree heights were measured at the beginning and end of each season in 1971, 1972, and 1973. After thermographs, total wind anemometers, and a rain gage were installed June 8, 1973, one season's measurements were taken. Wind velocity and air temperatures were measured at a height of 2 feet.

The solar still improved growth of redcedars 148 percent over the control and survival was the same, but because of problems with the Tedlar cover, after the first season we changed to a drip-irrigation treatment. For the drip-irrigation treatment, each tree was given 10 gallons of supplemental water per month. The system was arranged so that water was fed directly into the root zone, 12 inches below the soil surface.

Because of low survival rates, the gravel-mulch treatments were changed to straw-mulch treatments at the beginning of the third season because the gravel available at the site was a natural deposit containing some fine sand and soil particles that tended to form a crust on the surface and thus reduce water infiltration. No Scotch pines survived the first 2 years, whereas 50 and 30 percent of the redcedars survived in 1971 and 1972, respectively. Survival of controls for the same period was 50 and 10 percent for Scotch pine and 90 and 70 percent for redcedar. Straw then was spread at the rate of 4 tons per acre and anchored with a jute netting. The straw covered an area 25 feet wide by 60 feet long, centered on the tree row.

EXPERIMENTAL DATA AND OBSERVATIONS

The 6-mil polyethylene used on the water-harvest areas was torn and mutilated by the end of the first summer and totally blown away by the following spring. The second season an anionic asphalt emulsion was sprayed at a rate of 1,245 gal/acre on the harvest areas. The emulsion deteriorated and was nonexistent by the end of the following winter. The third year, a mixture of R-20 silicone (sodium methyl silionate in water) and Wicaloid 7035-AO was used to cover the harvest areas. This mexture--2.5 percent R-20 and 9.2 percent latex by volume in water applied at a rate of 5,600 gal/acre--produced a hard, impervious surface, which stood up very well throughout the summer. We do not yet know what the condition will be at the end of winter. Because of exposure, extreme temperature differential, and the expansive capabilities of the soil, it was difficult to find a simple workable treatment for the water-harvest areas.

The average growth and survival for 1973 and total growth and survival for the original trees are presented in table 1. Tables 2 and 3 summarize the climatic and moisture data taken during 1973. Rainfall for the recording period measured 11.92 inches, whereas the long-time average for the period was approximately 9.50 inches (table 2).

Temperature measurements indicate that average daytime temperature was lower for the control than for either the snowfence or shade treatments. That was expected for the snowfence, but it was not consistent with other shade data because of an oversight when temperature recording instruments were installed. The instrument for the shade treatment was placed 1 foot closer to the ground than were the two other instruments, which resulted in a higher daytime temperature and caused the mean temperature to be higher than it should have been. Nighttime temperatures were about as expected. The snowfence treatment had lower temperature than the control; whereas, the shade treatment had a higher temperature than either the snowfence or the control.

The snowfence area had an average wind reduction of approximately 50 miles per day; the control and shade treatments, 160 plus miles per day (table 2).

Available soil water in the top 36 inches of the soil profile averaged approximately the same for all treatments, except for the profile modification and mulch, which averaged 0.69 inch less and 1.27 inches more, respectively, than the six other treatments (table 3). At the time most samples were taken, the lower 2.5 feet of soil was near its field capacity, which would account for the small differences among treatments.

INTERPRETATIONS AND DISCUSSION

In keeping with the primary function of this study--to find a simple, effective way to improve growth and survival of trees for wind barriers in arid and semiarid locations--the two water-harvest, drip-irrigation, and snowfence treatments improved total tree growth and survival, and shade improved survival only, compared with a control. Gravel mulch and profile modification improved neither growth nor survival (table 1).

The two water-harvest treatments influenced total growth and survival of redcedar trees similarly. The 50- by 100-foot harvest area produced 32 percent more total growth than did the control; the 50- by 50-foot area, 31 percent more. Redcedar survival was 100 percent and

TABLE 1.--Total growth and survival of original trees planted in 1971, and average growth and survival of trees in 1973

Treatment	Redcedars				Scotch pines			
	Original trees		1973		Original trees		1973	
	Total growth 1/	Survival 1/	Growth	Survival	Total growth 1/	Survival 1/	Growth	Survival
	Inches	Percent	Inches	Percent	Inches	Percent	Inches	Percent
Water harvest:								
50- by 100-ft area	36.5	100	15.1	100	1.2	50	5.0	80
50- by 50-ft area	36.3	90	14.3	100	2.4	60	.6	70
Drip irrigation	2/ 33.1	2/ 90	14.5	100	2/ 1.9	2/ 90	.4	90
Snowfence protected	32.7	90	15.4	100	3.6	90	9.5	90
Control	24.9	70	11.1	90	0	0	0	10
Shade	23.0	100	9.9	100	2.3	90	.3	100
Profile modification	20.6	70	8.6	90	0	20	0	20
Straw mulch	3/ 6.8	3/ 20	1.3	70	3/ 0	3/ 0	1.0	10

1/ Includes only those trees originally planted in 1971, whereas 1973 data are for replants 1 and 2 years old.

2/ Includes 1 year solar still and 2 years drip irrigation.

3/ Two years gravel mulch and 1 year straw mulch.

TABLE 2.--Climatic data for field site, Colby, Kans., 1973

Date	Rainfall	Mean temperature			Wind		
		Control	Snowfence	Shade	Control	Showfence	Shade
	Inches	---Degrees Farenheit---			---Miles per day---		
June 8 to July 7	0.71	77.4	77.9	79.5	149.05	106.35	145.25
July 8 to August 6	4.55	74.5	75.3	75.9	134.40	97.90	140.90
August 7 to September 10	.75	78.2	78.9	79.9	168.68	114.12	162.20
September 11 to October 17	5.91	57.4	58.1	59.1	168.55	110.89	166.11

TABLE 3.--Average available water 1/ during 1973 in the top 36 inches of the soil profile

Date	Water harvest 50 by 100 ft	Water harvest 50 by 50 ft	Drip irrigation	Snowfence protected	Control	Shade	Profile modification	Straw mulch
1973	Inches							
June 8 to July 7	4.14	4.44	4.51	4.68	4.80	5.10	4.56	5.49
July 8 to August 6	4.17	4.17	3.93	4.00	4.45	4.64	3.46	5.44
August 7 to September 10	4.36	4.36	3.65	3.81	4.26	4.40	2.46	5.42
September 11 to October 17	3.89	4.31	4.01	3.86	4.91	4.27	3.21	5.81
Average	4.25	4.50	4.22	4.24	4.61	4.70	3.73	5.69

1/ Available water in inches = $\frac{(BD)\ (\%H_2O\ depth}{(D_w)}$ where BD = soil bulk density, $\%H_2O$ = $\%H_2O$ as measured minus $\%H_2O$ at wilting point, depth = depth in inches that $\%H_2O$ represents, and D_w = density of water.

90 percent in the 50- by 100-foot and 50- by 50-foot harvest areas, respectively. Compared to the control, the drip-irrigation and snowfence-protected treatment produced 25 and 24 percent more total growth, respectively, and each had 90 percent survival. Data for the Scotch pines were erratic and inconclusive. Survival and growth tended to be greater in the snowfence-protected and shaded treatments, although 90 percent of the original trees planted survived under drip irrigation.

It is difficult to explain the low survival rates on the mulch treatments. One explanation is that the gravel contained such a high percentage of fines that it sealed over and suffocated the trees. Another possibility is that the gravel contained some foreign matter that produced a toxicity in the soil that remained when the gravel was removed and the straw mulch applied. The plots will be relocated within the study site next year (1974) in hope of obtaining better results.

SUMMARY

Redcedar and Scotch pine trees were used to find a simple, workable method of supplying supplemental water or altering the microclimate to improve tree growth and survival rates in semiarid locations.

Out of seven methods used in this study, four improved growth and and five improved survival of redcedars. In two different-sized water-harvest areas, redcedars produced 31 and 32 percent more growth, and also survived better than the control. Drip-irrigation and snowfence-protected treatments produced 25 and 24 percent more growth in redcedars, respectively, and survival rate was greater. A shaded treatment did not increase tree growth, but redcedars had a greater survival rate.

Data indicated that Scotch pines did better in snowfence-protected and shaded environments, but results were erratic. No treatment can yet be considered satisfactory for practical application.

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MULTIPURPOSE SALT TREATED WATER HARVESTING SYSTEM 1/

G. R. Dutt and T. W. McCreary 2/

Arizona has vast acreages of land that, due to overgrazing, have become unproductive. Many of these areas currently support from two to four cattle per square mile of land surface. It has been pointed out in the past that such lands could be used to harvest water. With the public's concern over our environment, one criterion for public acceptance of large-scale water harvesting projects is that lands used for such purposes be productive and environmentally pleasing.

In addition, surface and ground water supplies are becoming degradated by salt, and desalinization is being proposed for the reclamation of return flow waters. Thus, large quantities of salt may be produced, and additional beneficial uses for it seem desirable. With the need for land and water reclamation in mind, the authors envisioned a multipurpose water harvesting system.

The requirements of the multipurpose water harvesting system are to: (1) collect water for use inside or outside the system, (2) increase the desired production of the land within the system, (3) provide an esthetically pleasing environment. Such a system is under development at the University of Arizona, Page-Trowbridge Experimental Range.

EXPERIMENTAL AREA

Climate and Soil

The elevation of Page Range is about 3,680 feet above mean sea level. Rainfall maps of the area place it in the 12-to 16-inch range. Summer to winter rainfall ratio is unity. A weather station, which includes temperature, relative humidity, and a recording range gage, was established to collect weather data at the site. The soil where the catchment area and cropped waterways are located is a Whitehouse loam. Soil analysis and moisture characteristics are given in tables 1 and 2.

Sodium Treated Catchment Area

An esstential component of any water harvesting system is the catchment area. A method of minimizing catchment area is to reduce infiltration of water into the soil. Methods long recognized for reducing infiltration are (1) increasing the "exchangeable sodium percentages;" (2) "puddling," or breaking down the soil structure; (3) eliminating vegetative cover; and (4) reducing ponded water (surface storage). To take advantage of the above, the soils in the catchment area for this study were treated in the following manner: (1) Native vegetation was removed and the area shaped and smoothed to about a 2- to 4-percent

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1/ Contribution from the Department of Soils, Water and Engineering, The University of Arizona Agricultural Experiment Station, Tucson. Journal Paper No. 2268.

2/ Professor and research technician, Department of Soils, Water and Engineering, University of Arizona, Tucson.

TABLE 1.--Physical characteristics of Whitehouse loam from the Page-Trowbridge Experimental Range

Depth (inches)	Sand	Silt	Clay	Moisture			Bulk Density
				Saturation	1/3 Bar	15 Bar	
	Percent	Percent	Percent	Percent	Percent	Percent	
0-3.0	45.7	32.8	21.5	27.66	9.26	3.72	1.35
3.0-8.5	39.2	32.6	28.2	26.21	9.20	4.68	1.66
8.5-15.0	2.2	20.5	77.3	66.50	31.61	20.08	1.77
15.0-19.0	20.5	21.8	57.7	48.58	25.45	13.96	1.81
19.0-31.0	46.8	19.2	34.0	33.73	16.55	9.03	1.82
31.0-42.0	19.5	46.5	34.0	44.19	19.43	8.81	1.67
42.0-44.0	38.0	29.7	32.2	42.10	16.68	8.15	1.65
44.0-60.0	40.5	33.4	26.1	30.91	12.03	4.92	1.65

TABLE 2.--Chemical characteristics of Whitehouse loam from the Page-Trowbridge Experimental Range

Depth (inches)	pH	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	NO_3	HCO_3^-	$CO_3^=$	$SO_4^=$	$SiO_3^=$	CEC 1/
		Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/l	Meg/100g
0-3.0	6.1	0.39	0.54	2.4	1.0	5.64	0.23	3.6	0	5.83	1.24	6.45
3.0-8.5	6.6	1.52	.27	3.8	1.4	8.46	.25	4.8	0	4.17	.94	7.74
8.5-15.0	7.0	4.61	.08	2.2	3.6	8.46	.19	5.6	0	5.83	.63	31.45
15.0-19.0	7.8	5.70	.12	2.2	1.0	8.46	.24	6.8	0	5.83	.39	21.16
19.0-31.0	8.0	8.91	.14	2.8	1.4	14.10	.24	3.4	0	8.33	.59	18.14
31.0-42.0	8.1	16.70	.18	4.2	2.8	16.92	.25	3.8	0	10.83	.99	16.52
42.0-44.0	8.1	16.39	.15	3.4	1.8	14.10	.24	4.8	0	12.50	1.35	13.15
44.0-66.0	8.2	12.56	.09	2.4	.4	11.28	.25	4.8	0	9.16	1.65	9.36

1/ With the exception of cation exchange capacity (CEC), analyses are from saturated paste and saturated paste extract.

slope; (2) soil structure in the surface 2 inches was reduced by rototilling; (3) 5 tons per acre of salt were added to the surface with a fertilizer spreader and mixed into the surface inch with a Harley rock picker; (4) the soil was compacted after two 0.4-inch rainstorms.

Cropped Waterway

Two 4-foot-wide waterways on 50-foot centers with a 2-percent grade were established between sodium treated catchment areas (see fig. 1). These waterways are used to (1) conduct water from the catchment areas to a water storing facility and (2) provide beds for plants. For best efficiency, a crop selected for use in these beds should have relatively low water use, ability to survive moderate drought, deep roots to maximize the use of stored soil moisture, and high economic value. The crop chosen for testing was wine grapes. Twelve varieties of wine grapes were obtained from California. The varieties were Cabernet Sauvignon, Pinot Noir, White Riesling, Chardonnay, Chenin Blanc, Zinfandel, Barbera, Gamay, Sauvignon Blanc, French Colombard, Ruby Cabernet, and Sylvaner. Three randomized blocks, containing 72 plants, were established in the cropped waterways during the summer of 1972. All but the French Colombard and Sylvaner were planted on May 26, 1972. These last two varieties were planted June 26, 1972. Twenty-four Barbera

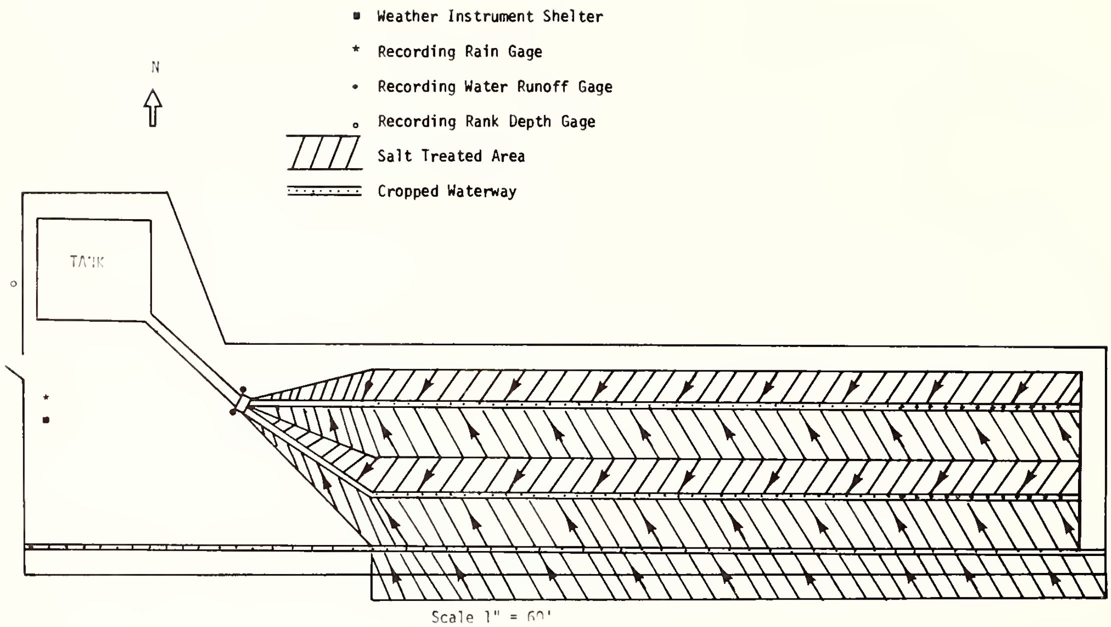
■ Weather Instrument Shelter
* Recording Rain Gage
• Recording Water Runoff Gage
∘ Recording Rank Depth Gage
Salt Treated Area
Cropped Waterway
N
TANK
Scale 1" = 60'

FIGURE 1.--Page Trowbridge Experimental Range salt-treated water harvest, grape and fruit tree plot.

vines were planted June 8, 1963. Spacing between vines along the waterway is 8 feet. The lower end of each waterway is provided with a recording H-flume for measuring runoff.

Adjacent Area

In addition to the main plot and cropped waterways described, a second cropped waterway and salt-treated area was developed adjacent to the south boundary of the main salt-treated area. This second system has a cropped waterway 4 feet wide and 600 feet long and a salt-treated area 30 feet wide and 400 feet long. Runoff from this treated area is used only as a water source for this secondary cropped waterway and is not stored in the water storage facility. In this cropped waterway, 57 deciduous fruit trees were planted. Three deciduous fruit trees were also planted in the main cropped waterway.

Three trees of each of the following varieties of deciduous trees were planted: Redspur Delicious Apple, Goldspur Delicious Apple, Thewgold Delicious Apple, Nured Jonathan Apple, Tydeman's Red Apple Bartlett Pear, D'Anjou Pear, Max-Red Bartlett Pear, Dwarf Bartlett Pear, Dwarf D'Anjou Pear, Early Redhaven Peach, Fairhaven Peach, Rosa Peach, Garden State Nectarine, Beauty Plum, Santa Rosa Plum, Riland Apricot, Sungiant Apricot, Blanhum Apricot, and Tilton Apricot.

Sodium Treated Tank

A tank, with a capacity of approximately 85,000 gallons, was then constructed at the lower end of the waterways (see fig. 1). The bottom and sides were treated with 5 tons per acre of salt. The salt was hand raked into the soil. A depth recorder was installed to measure water loss. During December 1971, the tank was covered with a polyethylene cover. Later, the cover was replaced with coupled-expanded-polystyrene, asphalt-chip coated (CEPAC) rafts.

Water Use

A 5-horsepower pumping unit was installed west of the tank and an irrigation system installed in the cropped waterways provided water during dry periods. Application of water is made to each vine and tree in the cropped waterways adjacent to the salt-treated runoff areas with one small spray head per vine. These spray heads deliver a fine spray in a radius of 3 feet and an arc of 180°. In addition to the main plantings in the waterways, water is also supplied to a wild game trough and seven table-grape vines grown over an arbor.

RESULTS

The runoff data for the period July 1, 1971, to December 30, 1971, have been evaluated. During this period, 14.23 inches of rainfall were recorded and 6.76 inches of runoff were measured at the H-flumes. Thus, 52.5 percent of the rainfall was collected in the tank. Monthly rainfall is given in table 3. Note that two drought periods occurred. Since December 1971, the tank has never been empty, even though there was considerable water use during the drought of 1973.

TABLE 3.--Monthly rainfall, in inches, at Page-Trowbridge Experimental Range

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1971	(1/)	(1/)	(1/)	(1/)	(1/)	(1/)	1.68	4.63	1.74	2.60	0.63	2.95	14.23
1972	0.0	0.0	0.0	0.0	0.3	1.74	1.25	1.98	1.70	5.64	2.13	1.18	15.92
1973	.28	2.43	2.99	.29	.72	.59	1.55	.35	.07	.0	.77	.0	10.04

1/ Not measured.

The seepage rate of the tank was found to be 0.09 inches per day during December 1971. The water loss from the tank with the rafts during December 1973 was 0.09 inches per day with the raft cover.

The salt content of the water in the tank at different dates is given in table 4. It appears that after initial establishment, the salt content declines. It is evident that the added chloride is remaining on the catchment.

The grape vines planted May 26, 1972, have shown good growth. Of the 60 vines planted, only one failed to survive. This vine was found to be wilted shortly after planting. The vines planted on June 26, 1972, showed only modest growth by the fall of 1972. Also, 3 of the 12 vines failed to survive. The variety that showed the best growth was Barbera. Thus, it was chosen for planting in a block in 1973. Of the vines planted June 3, 1973, four failed to survive; however, the losses were due to fire and poor planting technique.

Following treatment, a Rotadisk Rainulator was used to measure infiltration on the catchment. It was found that the terminal infiltration rate was essentially zero. On nine locations outside the treated area, the terminal infiltration ranged from 1.7 to 1.3 inches per hour.

ACKNOWLEDGMENTS

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TABLE 4.--Chemical composition of tank-held runoff water from Page-Trowbridge Experimental Range

Sample date	Total soluble salts	pH	Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	NO_3^-	HCO_3^-	$CO_3^=$	$SO_4^=$	$SiO_3^=$	Total N
	P/m		P/m	P/m	P/m	P/m	P/m	P/m	P/m	P/m	P/m	P/m	P/m
8/9/71	610	7.8	200	3.9	30	7	264	10.5	63	0	35	6	3.6
9/13/71	210	7.9	115	5.8	5	4	160	7.5	46	0	30	(1/)	2.4
9/30/71	293	7.6	90	4.7	7	1	132	7.5	37	0	18	(1/)	3.0
12/21/71	257	8.4	89	(1/)	2	1	124	1.5	29	0	10	(1/)	(1/)
9/18/72	257	7.2	72	(1/)	7	<1	92	.5	78	0	7	8.5	(1/)
10/9/72	219	8.4	62	(1/)	6	2	80	1.6	59	0	8	7.3	(1/)
11/24/72	239	7.0	40	(1/)	5	0	44	1.3	49	0	10	9.0	(1/)
5/3/73	154	7.0	37	(1/)	3	2	50	.1	34	0	20	8.0	(1/)
5/31/73	172	6.9	40	(1/)	5	3	55	1.1	42	0	20	6.5	(1/)
6/14/73	192	7.1	46	(1/)	8	2	59	.1	49	0	20	6.8	(1/)
7/20/73	180	7.4	47	(1/)	11	3	63	.1	34	0	22	.8	(1/)
8/6/73	210	7.2	50	(1/)	10	6	59	1.3	59	0	20	4.6	(1/)
9/6/73	216	7.9	49	(1/)	10	4	67	2.2	59	0	22	2.8	(1/)

1/ Not analyzed.

project is in cooperation with C. Brent Cluff and J. R. Kuykendall of The University of Arizona Water Resources Research Center and Department of Horticulture and Landscape Architecture, respectively.

DIFFERENT SOIL TREATMENTS FOR HARVESTING WATER FOR RADISH PRODUCTION IN THE MEXICO VALLEY

M. G. Anaya and J. S. Tovar [1]

INTRODUCTION

Dryland agriculture in the Mexico Valley occupies approximately 75 percent of the cropland area. Forages, grains, fruits, flowers, and vegetables are the principal crops grown. This region contains areas of favorable precipitation, such as Chalco in the southern part of the valley, which has an annual precipitation of 1,000 mm, and of unfavorable precipitation, such as Teotihuacan, in the northern part, where annual rainfall is scarcely 500 mm.

Better utilization of rainwater is essential, as is proper management of soil and crop factors. For this reason, the Soil Physics Section has initiated research on the experimental station of the National School of Agriculture, where annual precipitation is 650 mm. The objectives of the research are to evaluate crops that may be grown in place of corn and optimize, by economical methods, management of the soil, plant, and rainfall factors. This study presents the effects on radish production obtained by treating the soil surface with five different covers on three sizes of cultivated areas used to collect water.

In harvesting water, it is important to define the relationship between the water collecting area and the cultivated area to obtain the best management of soil and plant factors. Water harvesting systems must also consider frequency, duration, and amount of rainfall for several years, especially for crops with short vegetative cycles. In this type of agriculture, research has to be conducted for several vegetative cycles to find the best treatments in both water collective areas and crop growing areas.

Some researchers (1, 2, 4, 6) have studied the use of different methods to catch water, such as compacted earth; compacted earth. sodium treated; gravel covered plastic; asphalt-plastic, asphalt-chipcoated; compacted earth, diesel treated; concrete cover; crop residues; sheet metal; plastic covers; and so forth. This methodology has been applied on the contributing area; however, it is necessary to know if these will be permanent test areas and to find the most economical and efficient methods.

Since most water losses from agricultural land occur as runoff or evaporation, it is obvious that in order to get success in water harvesting methods, attention must be paid to managing runoff in the contributing areas and controlling evaporation in the cultivated areas. The size of contributing areas will depend upon precipitation, water holding capacity of the soil profile, and type, population, and geometry of plants.

Several methods have been developed to use runoff more efficiently in crop production. Myers (6) noted that collection of water is practiced in several ways: By covering soil with impermeable sheeting, by building contour ditches to collect hillside runoff, by modifying vegetation, by building pavement, and by treating soil to reduce its permeability. Zingg and Hauser (8) developed a method of shaping land so that the water stays where it falls or, alternatively, runs off from a slope to irrigate a level bench below the slope. Another approach to collecting water, mentioned by Evenari et al (3), involves increasing storage in the root zone in a region where precipitation is 100 mm. The water was collected in rectangular microcatchments and used for growing fruit trees and pasture shrubs. In Australia, a catchment to cultivated crop ratio of 25:1 increased yields of range plants by ponding off runoff water behind low earth banks (7). Luebs and Laag (5) compared three crop and water management systems in a winter rainfall climate by holding and inducing runoff.

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An inexpensive technique, developed in Chapingo, makes use of a small land leveler (2.5-m width), which follows the land contour. Results obtained are reported in this paper.

MATERIALS AND METHODS

The experimental site is located in the experimental field of the National School of Agriculture. The soil is a Nativitas sandy loam; the slope is 3 percent and the depth varies from 30 to 80 cm. Water holding capacity is 16.0 percent at 0.3 bar tension, 8.0 percent at 15.0 bars tension, 25.0 percent at saturation point, and has a bulk density of 1.4.

Two rain gages and two evaporometers were located in the experimental site to register daily rainfall and evaporation. Monthly evaporation varied from 110 to 100 mm from July to September, according to data of 1959-68. Mean monthly temperature during this period was about 14° Centigrade. Total rainfall in July, August, and September was about 330 mm.

The experimental site was prepared according to traditional methods of tillage: It was plowed, disked, and leveled. Small watersheds were constructed by using the natural slope of 3 percent and leveler, 2.5 m in width.

Plots were 2.5 by 7.0 m. Soil moisture content was determined, by the gravimetric method, every third day during the whole vegetative cycle at depths of 0 to 10 cm and 10 to 20 cm.

Five treatments were applied on runoff surfaces: Polyethylene cover, straw cover (1 kg/m^2), compacted earth (CE), CE diesel treated 250 ml/m^2, and CE diesel treated 125 ml/m^2 with the following approximate costs of treatment: 10, 3, 1, 1, and 0.5 cents/m^2, respectively. These treatments were combined with 25, 50, and 75 percent of the total cultivated area used to collect rainwater, giving 15 treatments arranged in a block seldom design. A check was also included, bringing the total to 16 treatments; three replications were established.

Seedling and harvesting dates were July 16th and September 7th, 1973, respectively. The variety used was Long Pink, applied as 5 g seed/m^2 in lines 62 cm apart. At harvesting time, the market price of radishes was 3 cents/kg.

RESULTS AND DISCUSSION

Soil Moisture Content vs. Treatments Studied

Data about the average soil moisture content in the 0- to 10- and 10- to 20-cm layers, obtained every third day, are given in tables 1 and 2. As the soil moisture content was very similar in both layers, an

TABLE 1.--Soil moisture content in the cultivated area vs. treatments on the water harvesting areas 1, 15, 35, and 55 days after seeding date

Soil surface treatment	Percentage of area used to harvest rainwater per day(s) following seeding date 1/															
	0				25				50				75			
	1	15	35	55	1	15	35	55	1	15	35	55	1	15	35	55
	Percent															
Polyethylene cover					14.9	13.7	17.7	14.6	13.2	13.4	15.7	15.7	15.9	15.7	19.3	17.4
Straw cover					12.2	12.6	14.8	13.2	16.1	13.8	14.4	15.0	14.7	14.1	13.5	14.2
Compacted earth (CE)					11.5	11.8	14.2	14.6	14.6	13.0	15.5	15.1	15.1	13.0	16.0	15.1
CE diesel treated 250 ml/m^2					10.5	12.6	14.3	16.1	10.8	11.7	16.3	15.4	10.8	11.9	16.0	14.3
CE diesel treated 125 ml/m^2					13.2	13.3	15.3	14.8	13.6	13.6	16.8	15.1	13.2	14.1	16.9	15.2
Check	11.6	10.6	13.2	12.2												
Average					12.5	12.8	15.3	14.7	12.8	13.1	15.7	15.3	13.9	13.8	16.3	15.2

1/ The average rainfall between the 1st and 15th days was 4mm; between the 15th and the 35th, 7 mm, and between the 35th and 55th, 5 mm.

TABLE 2.--Percentage of available moisture in the cultivated area vs. treatments on the rainwater harvesting 1, 15, and 55 days after seeding date

Soil surface treatments	Percentage of area used to harvest rainwater per day(s) following seeding date															
	0				25				50				75			
	1	15	35	55	1	15	35	55	1	15	35	55	1	15	35	55
	Percent															
Polyethylene cover					87	71	14	83	65	68	96	96	99	96	141	118
Straw cover					53	58	85	65	101	73	80	88	84	76	69	78
Compacted earth (CE)					44	48	78	83	83	63	94	89	89	63	100	89
CE diesel treated 250 ml/m^2					32	58	79	101	35	46	104	93	35	49	100	79
CE diesel treated 125 ml/m^2					65	66	91	85	70	70	110	89	65	76	111	90
Check	45	32	65	53												
Average					56	60	91	84	60	64	96	91	74	73	104	90

average was obtained, which showed a direct relation to the rainfall during the vegetative cycle of radish, as can be seen in table 1.

The soil moisture content in all the plots showed practically no increments during the first 15 days after seeding date, probably because the average rainfall in this period was 4 mm and the estimated consumptive use was 4.5 mm. However, in the period between 15 and 35 days, such increments were approximately 50 percent because the average daily rainfall was 7 mm and the consumptive use was 6.5 mm. After this period (between 35 and 55 days), a decrease of about 10 percent in the soil moisture content was observed due to the average daily rainfall of 5 mm. The same happened with the available water as can be observed in table 2. The available moisture in the cultivated area fluctuated between 32 in the check and 141 percent with the polyethylene cover.

Water Efficiency in Radish Production

Total precipitation during the vegetative cycle of 57 days was 299 mm, distributed in 42 rainfalls. Assuming 100 percent runoff with all covers, the following yields and water use efficiencies were obtained when 0, 25, 50, and 75 percent of the total area were used to collect rainwater:

Percentage of area used to collect rainwater	Estimated consumptive use	Radish yield	Water use efficiency
	Mm	Ton/ha	Kg/mm-ha
0	322	32.7	111
25	322	55.7	166
50	322	63.5	190
75	322	76.7	242

As the available moisture in the check treatment varied between 32 and 65 percent during the vegetative cycle and averages of the other treatments varied from 56 to 104 percent, differences in yields and water use efficiencies between check and other treatments of water harvesting, where the moisture was more available for radish growth, are obvious. As the treatments of compacted earth (CE), CE diesel treated 250 ml/m^2, and CE diesel treated 125 ml/m^2 produced yields very similar to that of the polyethylene cover, 100 percent runoff could be assumed with these soil surface treatments. The contrary happened with straw cover because some rainfall infiltrated below the straw, and harvested water in the cultivated area was less, as indicated by the decrease of radish yield.

Radish Yield

Effects of five different soil surface treatments and three areas used to collect rainwater are reported in table 3. Yields of radish considered only production on the cultivated areas, not those areas with different covers. In this way, it is possible to analyze effects of additional water from runoff. No significant differences in radish yields were obtained with the five treatments studied, indicating that the most recommendable treatments would be compacted earth (CE) or CE diesel treated 125 ml/m^2, which are the most economical considering costs per square meter.

In analyzing effects of runoff when 25, 50, and 75 percent of

TABLE 3.--Yield of radish (Raphanus sativus, var. Long Pink) obtained with 5 soil surface treatments in 3 cultivated areas used to collect rainfall

Soil surface treatments	Yields of radish for the following percentages of areas used to collect rainwater			
	25	50	75	Average
	Tons/ha	Tons/ha	Tons/ha	Tons/ha
Polyethylene cover	55.65	63.50	76.72	65.29
Straw cover	48.22	59.00	64.36	57.20
Compacted earth (CE)	54.28	60.58	78.80	64.56
CE diesel treated 250 ml/m^2	49.82	61.86	79.04	63.57
CE diesel treated 125 ml/m^2	54.78	61.45	77.64	64.62
Average 1/	52.55	61.28	75.32	

1/ Check yielded 36.66 ton/ha with no soil surface treatment and no area dedicated to harvest rainwater.

cultivated areas were used to collect rainwater, increments compared with check treatment (36.66 ton/ha) were 43, 67, and 106 percent, respectively. Results obtained showed a tremendous response to radish to additional collected rainfall and the economical advantages of growing this crop instead of the traditional corn.

CONCLUSIONS

Technical viability of radish as an economical alternative for corn was demonstrated.

Treatments applied to soil surfaces did not show significant differences; for economy, it would be desirable to select the cheapest ones.

The more surface used for runoff, the higher the production of radish obtained on the three levels studied.

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DISCUSSION

SESSION V--Ron Reeves, Chairman

L. WILLARDSON: What is the quality of highway runoff for livestock and forage production?

D. WOOLHISER: This aspect should be considered. We have no data on the quality of runoff water from highways or on possible concentrations of combustible products in roadside vegetation. However, a speaker at this symposium showed a stock water pond fed from highway runoff, and apparently the livestock are suffering no ill effects. There is also research undergoing at Colorado State University, and possibly other institutions, analyzing roadside soils and forages for concentrations of lead and possibly other elements.

M. FAIRBOURN: Did you place your gravel mulch treatment around the stems of your trees? Were the largest grains of your mulched soil larger than the smallest grains of your gravel mulch?

J. DICKERSON: We did not intentionally place the gravel around the trees, but due to shifting cover by hard rains, the gravel did enclose the tree stems. A mechanical analysis was not made on the gravel, but we would say that they were.

L. BRAZELL: What is the longevity of salt treatment for sealing soil?

G. DUTT: A plot in my backyard has been in 6 years with no breakdown yet.

C. CLUFF: Could you comment on the possibility of going into sodic areas and strip treating with gypsum to provide a planting area? In effect, it would be a reverse treatment but accomplish the same purpose as a salt-treated water harvesting treatment.

G. DUTT: I see no reason why this would not be possible. It would be less expensive than a salt-treated catchment.

D. FINK: Do you foresee excessive salt movement in the soil (with time), which will eventually kill off your grapes?

G. DUTT: No, the salt is entrapped, to a large extent, on the catchment. The water irrigating the grapes should be more than adequate to leach the cropped waterways.

G. FRASIER: Have you done any hydrologic analysis in catchment size to the required consumptive use?

G. DUTT: Only to a limited extent. Such a treatment is one of the objectives of our work.

R. MICKELSON: What was the average slope of the salted catchments? What was the degree of soil erosion from the catchment, if any?

G. DUTT: The slope is 1 to 2 percent. Erosion has not been measured, but appears moderate to small.

CONCLUDING REMARKS

Gary Frasier

At the close of the final session of technical paper presentation, the Symposium was opened to general discussion. Several participants addressed the Symposium to comment on or add to the papers presented. The following is a brief summary of these remarks.

Dave Wisdom, from Honolulu, commented that his company has installed over 300 catchments and/or storage units, utilizing artificial rubber sheeting. They have found that their biggest problem is preventing uplift of the membranes by wind. He also stated that if the materials are improperly installed, adequate life can not be achieved. Maintenance is essential to the success of an installation, and costs must be included in economic analyses. In his opinion, maintenance-free materials are not yet available.

Allen Dedrick, of the U.S. Water Conservation Laboratory, briefly described results of some wind tunnel work he performed on the aerodynamic uplift potential over catchments and reservoirs. The location and magnitude of these potential uplift forces could be estimated. Design criteria to minimize aerodynamic uplift were developed.

Charles Staff, from Upper Montclair, N.J., commented that, in his experience, the biggest problem with reservoir linings has been mechanical damage from animals, wind, and man. Many of these problems can be reduced by placing a soil cover over the lining.

Hugo Velasco, from Monterrey, Mexico, said that water harvesting and runoff agriculture are potentially feasible in a large area of Mexico. The major deterrent, at present, is the cost of collecting and storing the water.

Adrian Hardan, of Bagdad, Iraq, observed that in many areas water harvesting can mean the difference between life and death and that the economic aspects are thus of minor importance in these cases. He also raised the question of water harvesting in areas with extended drought and stressed the importance of additional water resources, for example, ground water. He suggested that a coordinated, international scientific effort is needed to develop the various systems of water harvesting that can be used on a worldwide scale. He suggested that large water harvesting projects may not be as feasible as many smaller units designed for specific conditions.

Malcolm Hollick, of the University of Western Australia, commented that the economy of Western Australia would not be able to support the type of systems presently used in much of the United States. He thinks the users of water harvesting in Western Australia are fortunate to have a source of clay available at shallow depths which is used to seal surfaces of roaded catchments and contributes to their performance.

Richard Shaw, retired from the University of Arizona, noted that he has been able to minimize the aerodynamic uplift of a plastic membrane on a catchment by the use of strategically located ventilators that had been furnished by Charles Staff. These ventilators created a partial vacuum under the sheeting. Staff then elaborated on his experience with the ventilators.

C. Brent Cluff, of the University of Arizona, commented that in some situations a soil cover over a reservoir lining can reduce seepage losses through small holes.

Robert Nulsen, of Western Australia, commenting on microwatersheds and runoff farming, stated that plants should be developed to make the maximum use of the collected water.

Lloyd Myers, Agricultural Research Service, Berkeley, Calif., observed that progress is being made in many areas, such as precipitation prediction, which is not normally considered a part of water harvesting but is an important design factor. He believes the future potential of water harvesting is just starting to be recognized.

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